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LUBRICITY PROPERTIES OF HIGH-TEMPERATURE JET FUELS

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QUARTERLY REPORT NO. 10

15 August - 15 November, 1967

CONTRACT NO. AF33 (615)-2828

FOR

Air Force Aero Propulsion Laboratory

Air Force Systems Command

Wright-Patterson Air Force Base, Ohio

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FOREWORD

This report was prepared by the Advanced Lubrication Project, Products Research Division, Esso Research and Engineering Co. at Linden, N.J. under Contract AF33 (615) 2828. This program is administered by the Air Force Aero Propulsion Laboratory, Research and Technology Division, Air Force Systems Command with Art[illegible] [illegible]evenstein, Capt., USAF as coordinator.

This report covers work conducted from 15 August, 1967 to 15 November, 1967.

ABSTRACT

The Micro-Ryder gear test was evaluated as a possible test device for jet fuels. Although it correctly assessed the effect of additives and atmosphere it was too severe to detect differences between highly-refined and conventionally-refined fuels.

Scuffing tests generally agreed with earlier wear tests in assessing the effects of fuel composition and operating variables. However, some differences were found: some sulfur compounds reduced scuffing, whereas they had not reduced wear; scuffing is frequently more severe in dry argon than in wet air, whereas in wear tests this was reversed. Water appears to be the important factor reducing scuffing.

K-Monel showed some major differences from steel, even stainless steels. Specifically: (1) it scuffs easily in dry argon; (2) only the additive ER-3 was an effective lubricity additive and (3) in wet air oleic acid was actually a pro-scuff agent.

Abrasive wear was briefly studied. In the vane pump test, abrasive wear can be the major cause of wear. It is sensitive to the kind and amount of abrasive particles, but no general correlation could be found with particle size, hardness, or crystal structure, or concentration. Oleic acid can eliminate abrasive wear.

I. INTRODUCTION

The performance of jet fuels in friction and wear tests has been shown to be a complex phenomenon. Highly-refined fuels, consisting almost entirely of paraffinic and naphthenic hydrocarbons, have very poor lubricity. This can be restored by adding heavy aromatics (such as methylnaphthalene) or surface-active additives.

Most of the past work has been with steel, which is subject to corrosion by atmospheric oxygen. Indeed, corrosive wear (oxidative wear) appears to be the most serious form of wear encountered. Blanketing the system with an inert gas frequently reduces wear to zero. Water vapor also is important: if oxygen is present, it accelerates corrosive wear.

Besides corrosion, two other kinds of wear may be important: abrasion and scuffing. Abrasive wear is caused by hard particles suspended in the oil which scratch the metal surfaces. These hard particles can be iron oxides formed by corrosion. Thus corrosive wear can trigger abrasive wear. This report gives a brief account of abrasive wear in the Vickers vane pump, with some unexpected results.

Scuffing comes about when the surface coating (oxide or adsorbed film) is ruptured, leading to cold-welding and metal transfer. It is a high-load phenomenon, and not well understood. Research has therefore been carried out at higher loads to determine the effect of various additives on scuffing. These results are reported herein.

Corrosive wear has also been studied further, using metallurgies that are resistant or inert to corrosion. The mechanism of corrosive wear is thereby confirmed.

In addition, the Micro-Ryder gear test has been examined as a possible test device.

II. EVALUATION OF MICRO-RYDER AS A TOOL FOR STUDYING JET FUEL LUBRICITY

A. Introduction

Because of wide appeal of a gear test for evaluating the load-carrying capacity of fuels and lubricants, it was desirable to evaluate jet fuels in this type of test. Previous results have shown that the standard Ryder gear test is not altogether satisfactory (see second Quarterly Report in this series 15 August - November, 1965). A program was therefore set up to evaluate the Micro-Ryder gear test as a jet fuel lubricity tester. Our conclusion is that this test device is not suitable for jet fuel testing.

The Micro-Ryder is just what the name implies. It is a smaller version of the standard Ryder gear. Several of the drawbacks for the larger Ryder are not found in the smaller Ryder. For example, the slave gears are loaded by means of air pressure rather than gear oil; thus, test fuel cannot be contaminated. Also, much smaller quantities of test fluid are needed (35cc vs several gallons); thus, certain pure hydrocarbon types and lubricity additives which have been found useful in jet fuels may be very easily tested in the Micro-Ryder. It remained for this study to investigate the reproducibility of the Micro-Ryder as well as its sensitivity toward jet fuels of various lubricity characteristics.

B. Modifications To Micro-Ryder

As mentioned, the Micro-Ryder is a smaller version of the standard Ryder gear test machine. In order to use the Micro-Ryder for fuels testing, several modifications had to be made. Due to the extreme severity for fuels, tests of 2-minute duration were run at each load, rather than the standard 10 minutes. In addition, the equipment was modified to measure air pressures of several millimeters of mercury. This modification was made because, for the range of air pressures indicated on the machine, the gear loading was too high; a large amount of scuffing occurred at the lowest load, 1 psi. Tests were also run in an argon atmosphere as well as in room air.

C. Experimental Results

The Micro-Ryder was not able to detect the difference in lubricity of two non-additive fuels. Figure 1 shows data on a highly refined fuel, Bayol 35, and a conventionally refined fuel, RAF-176-64. This figure is a plot of the percent scuff as measured by microscopic examination of the gear teeth versus the applied load in lbs/inch of tooth width. Normally, one rates Ryder gear data by noting the load at which 22.5 % scuff occurs. As seen in the figure, Bayol 35 and RAF-176-64 appear equivalent at the 22.5% scuff point. At higher loads, the conventionally-refined fuel actually looks worse than the highly-refined fuel. These findings are in direct contrast to those found previously with other wear testers. Bayol 35 had been shown to be much poorer than RAF-176-64 in lubricity. This is shown in Table 1, which compares the scuff load at 22.5% scuff in the Micro-Ryder test with wear data from other testers used in this program. In the ball-on-cylinder device, 4-Ball wear test, and Vickers vane pump, Bayol 35 was definitely inferior to RAF-176-64. In the Micro-Ryder test it was not.

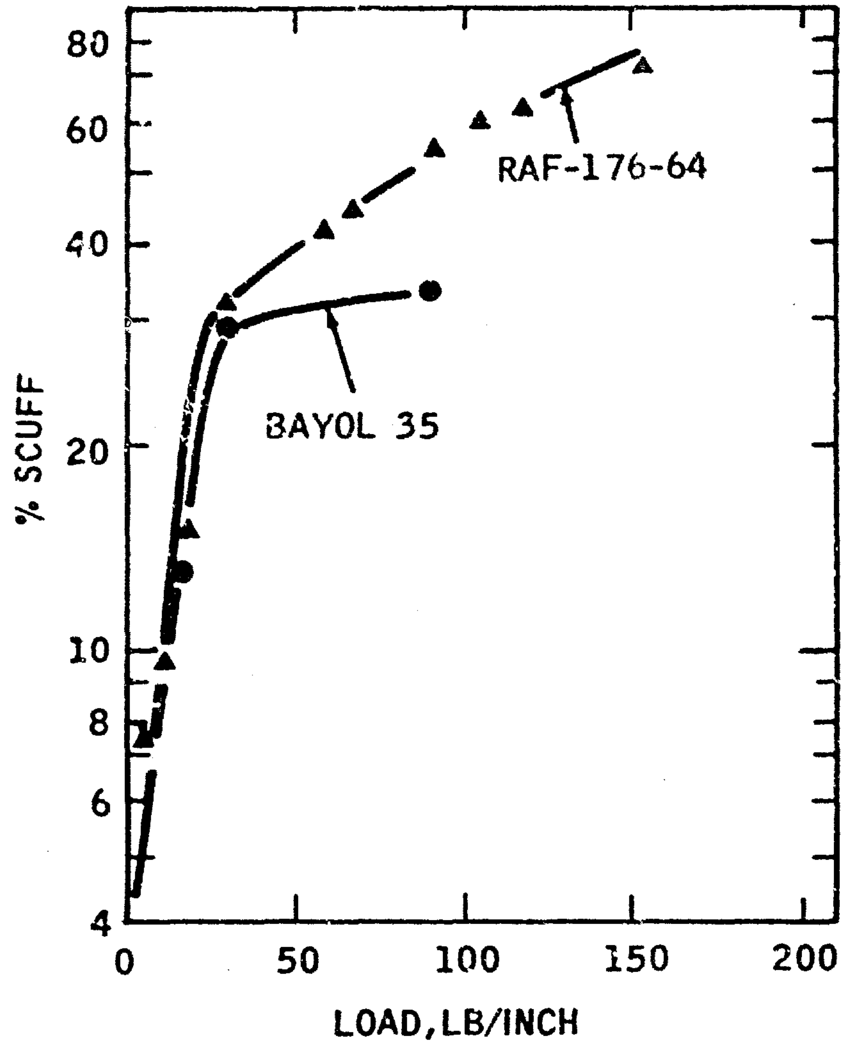


FIGURE 1 - MICRO-RYDER GEAR TESTS ON BAYOL 35 AND RAF-176-64 JET FUELS (77F, ROOM AIR, 2-MINUTE INTERVALS)

TABLE 1

COMPARISON OF WEAR TESTERS WITH MICRO-RYDER

	Bayol 35	RAF-176-64
Ball-on-Cylinder WSD, mm	0.63	0.38
4-Ball Test WSD, mm	0.80	0.61
Vickers Vane Pump Vane WL, mg	204	0
Micro-Ryder Test Scuff Load, #/inch	27	18

The effect of a lubricity additive in the Micro-Ryder test was also examined. Figure 2 gives data on 0.1% of ER-3 to Bayol 35 using room air atmosphere. The effectiveness of ER-3 is readily seen in the Micro-Ryder, as Bayol 35 plus the additive exhibits about eight times the load-carrying capacity of Bayol 35 alone. This comparison is made at the 22.5% scuff point. This result is in agreement with previous data obtained on the standard Ryder gear earlier in the program.

The effect of atmosphere (Figure 3) also is in agreement with previous findings, i.e., better performance with Bayol 35 is found in inert gas environment.

At first, it was planned to use the Micro-Ryder to measure gear scuffing at high temperatures in both air and inert atmospheres. In order to estimate the severity of the Micro-Ryder at elevated temperatures, a low viscosity liquid, normal heptane, was tested at room temperature. Heptane at room temperature has a viscosity of 0.43cp, which is the viscosity of Bayol 35 at 300F. Thus, just the viscosity effect alone can be estimated by comparing heptane with Bayol 35 in an argon atmosphere. This is shown in Figure 4. Two points are to be made here. First, if a test were run at 300° in an argon atmosphere with Bayol 35, the data would exhibit the trend shown by the heptane curve in Figure 4. That is, with no oxidation occurring (argon atmosphere) only the viscosity effect would show up at the higher temperature. The second point is that the Micro-Ryder is even more severe for the lower viscosity fluid. At less than 0.5psi applied load, the scuffing rose immediately to 22.5% with heptane. Therefore, testing jet fuels such as Bayol 35 at higher temperatures would make the severity of the Micro-Ryder worse than it is at room temperature.

D. Conclusions

The Micro-Ryder test is too severe for fuels testing. The failure of the Micro-Ryder to rate Bayol 35 and RAF-176-64 correctly may be due to running tests at loads below which it was designed. At these low loads, the test is apparently insensitive to fuels of various lubricity characteristics. On the other hand, additive and atmosphere effects agree with previous findings.

No additional work with the Micro-Ryder is planned since it is apparently too severe for fuels testing. However, the viscosity data indicate that the Micro-Ryder might be suitable for testing fluids in the lubricating oil range, that is, higher viscosity fluids.

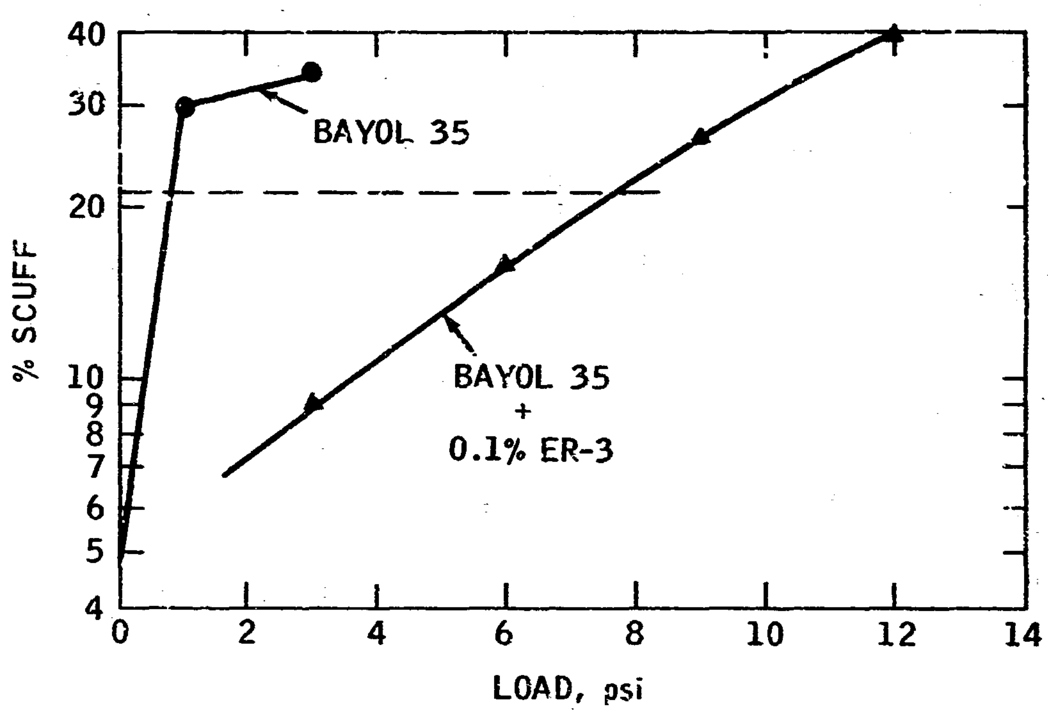


FIGURE 2 - EFFECT OF ADDITIVE IN MICRO-RYDER TEST
(77F, ROOM AIR, 2-MINUTE INTERVALS)

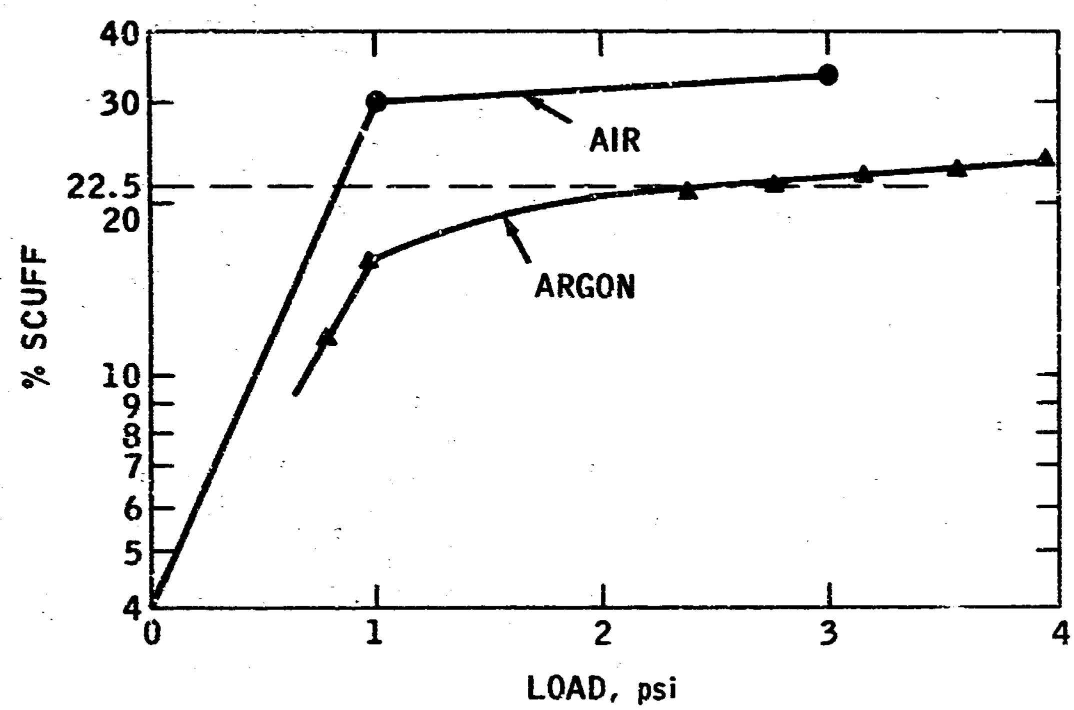


FIGURE 3 - EFFECT OF ATMOSPHERE IN MICRO-RYDER TEST
(77F, BAYOL 35, 2-MINUTE INTERVALS)

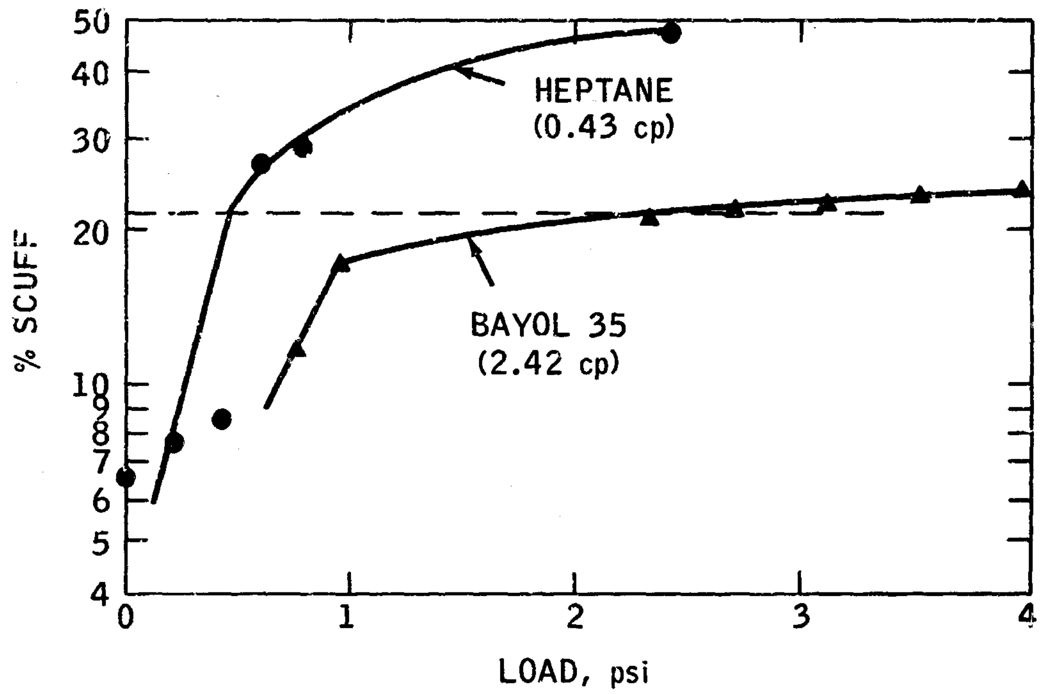


FIGURE 4 - EFFECT OF VISCOSITY IN MICRO-RYDER TESTS
(77F, DRY ARGON, 2-MINUTE INTERVALS)

III. SCUFFING OF STEEL - EFFECTS OF ADDITIVES

Most of the previous work was carried out at low loads, deliberately so that scuffing would not occur. Under these conditions, various additives were found to be good antiwear agents. One of the best was oleic acid; corrosion inhibitors and special lubricity additives were also very effective.

Inasmuch as scuffing is one of the important modes of wear, some tests have now been run to assess the effects of additives under scuffing conditions. Scuffing was accentuated in the four-ball test by running at elevated temperatures (240F), and in the ball-on-cylinder test by running at a high load (4kg). These test results indicated that most lubricity additives are good antiscuff agents as well, and that their effectiveness is dependent upon the atmospheric environment. In general, the additives were more effective in wet air than in dry argon.

A. Four-Ball Tests

Scuffing was determined in the four-ball test using the conventional procedure. A series of tests at increasing loads were run and the resulting wear scar diameter plotted against load. Scuffing is evidenced by a sudden increase in scar size; the load at which this occurs is the scuff-load. Usually scuffing was accompanied by an erratic friction trace and a loud chattering noise. At very high friction, the motor's overload trip would stop the test. This is termed "seizure."

In all cases the tests were run under a controlled atmosphere, usually either dry argon or wet (saturated) air. The temperature of 240F was chosen to give the most severe conditions without encountering excessive evaporation of the fuel sample.

1. Commercial Fuels

Figure 5 shows that a conventionally-refined fuel, RAF-176-64, gave a higher scuffing load than a highly-refined fuel, PW-523. PW-523 scuffed at 1 kg and seized at 3kg; RAF-176-64 was satisfactory at 5kg. This agrees with the wear data obtained in the ball-on-cylinder device at lower loads.

2. Additives

The scuffing tendencies of various lubricity additives is given in Table 2. The additives were evaluated at 50ppm in PW-523, in both dry argon and wet air. In argon, only ER-3 had any appreciable effect on scuffing. It increased the scuff load from 1 kg to 4-5kg. Other additives--ER-1, ZnDDP, and oleic acid--were completely ineffective. In wet air, the additives were somewhat better. Figure 6 shows that both oleic acid and ER-3 prevented scuffing out to 15kg. This behavior agrees with literature findings that acidic-type additives are most effective where an oxide coat is present.

ER-1 and ZnDDP were much less effective. Some scuffing occurred with ZnDDP at loads as low as 2kg, but the friction never became high enough to cause seizure even at 7kg.

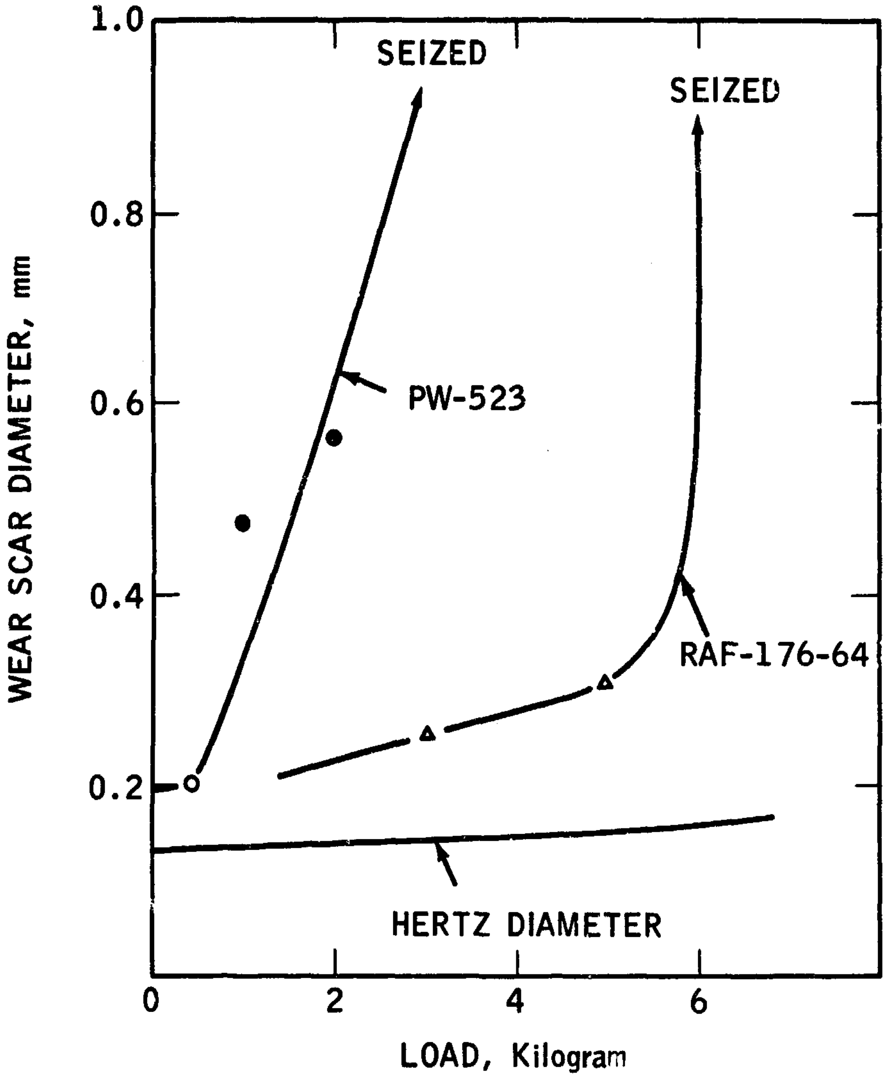


FIGURE 5 - SCUFFING LOAD FOR COMMERCIAL FUELS IN ARGON
(FOUR-BALL TESTS - 240F, 1200RPM, 52100 STEEL, 15 MIN.)

TABLE 2

EFFECT OF LUBRICITY ADDITIVES ON WEAR

(Four-Ball Tests, 1200rpm, 240F, 15 Min.)

Base Fuel: PW-523

	Dry Argon								Wet Air							
Load, kg:	0.5	1	2	3	5	7	10	15	0.5	1	2	3	5	7	10	15
Wear Scar Diameter*																
None	0.20	0.48	0.56	-	-	-	-	-	0.72	0.78	-	-	-	-	-	-
50ppm ZnDDP	-	0.20	0.68	S	-	-	-	-	-	0.20	0.75	0.80	-	0.88	-	-
50ppm Oleic Acid	-	0.24	-	0.62	S	-	-	-	-	0.22	0.23	0.38	0.42	-	0.45	0.43
50ppm ER-1	-	0.20	0.53	0.58	S	-	-	-	-	0.48	0.53	0.58	0.61	-	0.66	S
50ppm ER-3	-	0.20	-	0.27	0.69	S	-	-	-	0.30	-	0.38	0.61	0.57	0.52	0.57
Coeff. of Friction																
None	0.15	**	**	-	-	-	-	-	**	**	-	-	-	-	-	-
50ppm ZnDDP	-	0.15	**	***	-	-	-	-	-	0.10	**	**	-	**	-	-
50ppm Oleic Acid	-	0.17	-	**	***	-	-	-	-	0.10	0.11	0.17	0.12	-	0.13	0.12
50ppm ER-1	-	0.14	**	**	***	-	-	-	-	0.11	0.17	**	**	-	**	***
50ppm ER-3	-	0.14	0.13	0.12	**	***	-	-	-	0.2	-	0.17	0.12	0.14	0.13	0.11

* "S" indicates seizure.

** Erratic friction and chattering noise.

*** Friction off-scale.

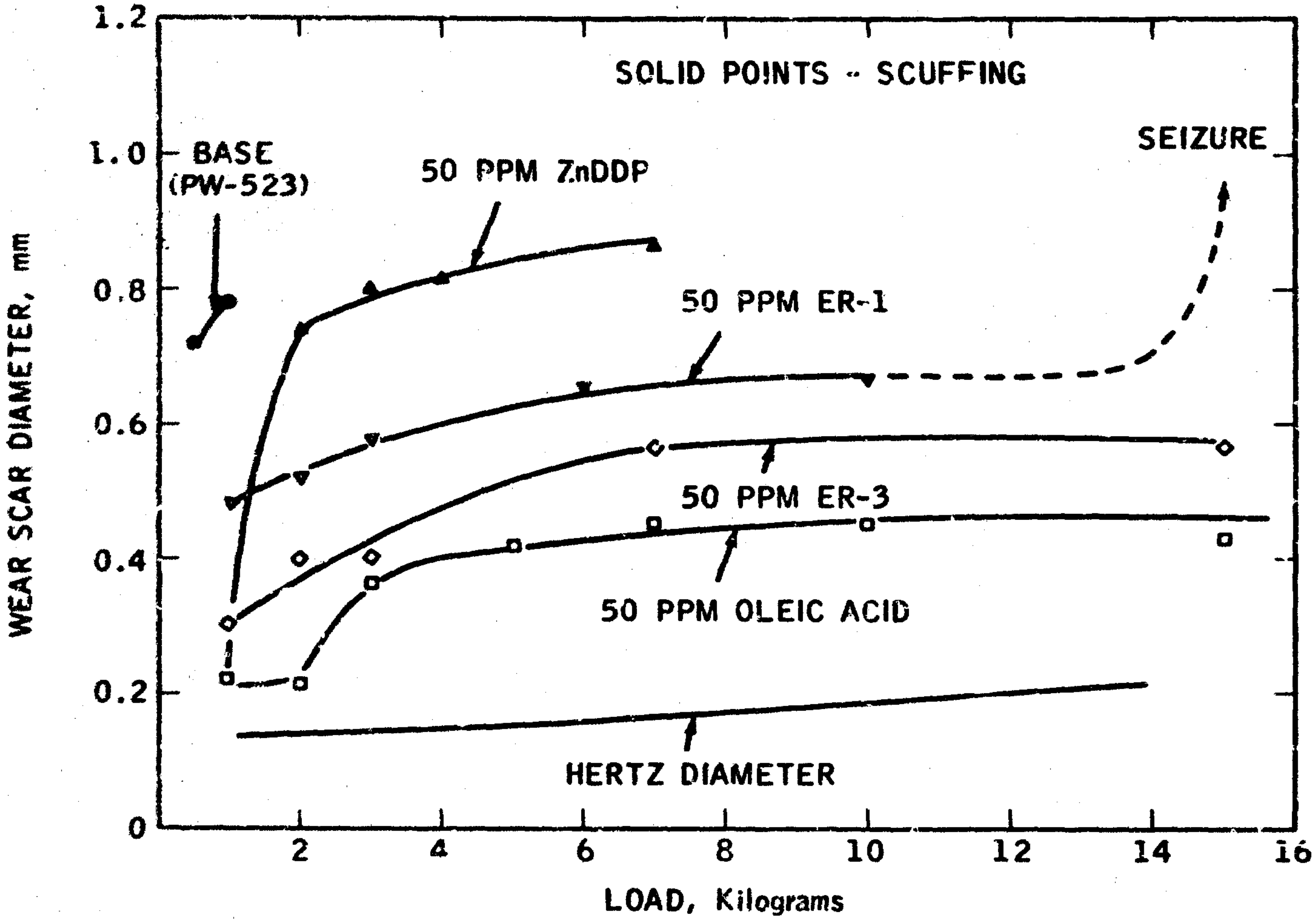


FIGURE 6 - EFFECT OF ADDITIVES ON SCUFFING LOAD IN WET AIR
(FOUR-BALL TESTS - 240F, 1200RPM, 52100 STEEL, 15 MIN.)

It is important to note that wear was almost always higher in wet air than in dry argon, but when scuffing occurred, it was usually at lower loads in dry argon. The effect of the additives was to decrease corrosive wear (and the resulting tendency to scuff), but to then expose the fact that a dry inert atmosphere leads to scuffing.

3. Hydrocarbons

Several hydrocarbons had been shown to be good antiwear agents in paraffinic fuels. These include olefins like dodecene and aromatics such as methylnaphthalene and indene. The scuffing performance of these hydrocarbons, as 5% blends in Bayol 35, is given in Table 3, and illustrated in Figures 7 and 3. Dodecene had almost no effect, but the two aromatics were roughly as good as the lubricity additives--although of course the concentration was far greater. Both methylnaphthalene and indene increased the scuff load from about 1 kg to 8-10kg in both dry argon and wet air. Again, with the aromatic blends, scuffing occurred sooner in dry argon than in wet air.

The effect of atmosphere on scuff load is summarized in Table 4. For paraffinic fuels without additives, scuffing occurs in wet air before it occurs in dry argon. This is the effect noted earlier--that corrosive wear can lead to scuffing. The effect of additives or aromatics is to give a modest increase in the scuff load in dry argon, but a major increase in wet air. Thus, scuffing of these blends occurs sooner in dry argon than in wet air. It seems most probable at present that the scuffing in dry argon is due to the lack of water rather than to the lack of oxygen. If this is true, the best performance should be in wet argon. This will be tested in future work. The effect of concentration will also be examined.

B. Scuffing Temperature in Ball-on-Cylinder Test

The determination of scuff load in the four-ball test is a time-consuming operation, involving several separate tests. An alternative procedure was to increase the load smoothly until scuffing occurred. The Roxana four-ball machine is ideally suited for this, for the load is applied pneumatically. However, this procedure was not satisfactory. Reproducibility was extremely poor and the scuff load was always far higher than obtained with the separate-test method.

Another approach was to run the ball-on-cylinder test at constant load but to increase the temperature until scuffing occurred. Scuffing was evidenced by high friction and severe chattering noise. This technique was not entirely successful, but it revealed some interesting facts.

The tests were carried out in dry argon only. The fuel sample was preheated to 120F, and during the test the temperature rose continuously at a rate of about 10F/minute. If no scuffing had occurred at 350F, the test was stopped. The total test time was therefore about 25 minutes.

Figure 9 shows the behavior of Bayol 35 in this test. At 240g, no scuffing was obtained up to 350F. At 2000g and 4000g, scuffing was complete as soon as it occurred at all. However, at 1000g the scuffing behavior was intermediate: friction rose somewhat more slowly, and then leveled off before final failure. This run was repeated, but the test was stopped at the high friction

TABLE 3

SCUFFING TENDENCIES OF HYDROCARBONS

(Four-Ball Tests, 1200RPM, 240F, 15 Min.)

Base Fuel: Bayol 35

	Dry Argon						Wet Air				
Load, kg:	1	3	5	8	10	13	1	3	5	8	10
Wear Scar Diameter ***											
None	0.28	0.71	3	-	-	-	0.83	S	-	-	-
5% Dodecene-1	0.25	0.30	S	-	-	-	0.72	0.62	-	-	-
5% 1-Methylnaphthalene	-	-	0.33	-	0.75	S	-	-	0.40	-	0.43
5% Indene	-	-	0.28	0.30	S	-	-	-	0.27	-	0.39
Coeff. of Friction											
None	0.22	*	**	-	-	-	*	**	-	-	-
5% Dodecene-1	0.16	0.13	**	-	-	-	*	*	-	-	-
5% 1-Methylnaphthalene	-	-	0.15	-	0.12	**	-	-	0.16	-	0.13
5% Indene	-	-	0.12	0.11	**	-	-	-	0.12	-	0.12

* Erratic friction and chattering noise.

** Friction off-scale and seizure occurred.

*** "S" indicates seizure.

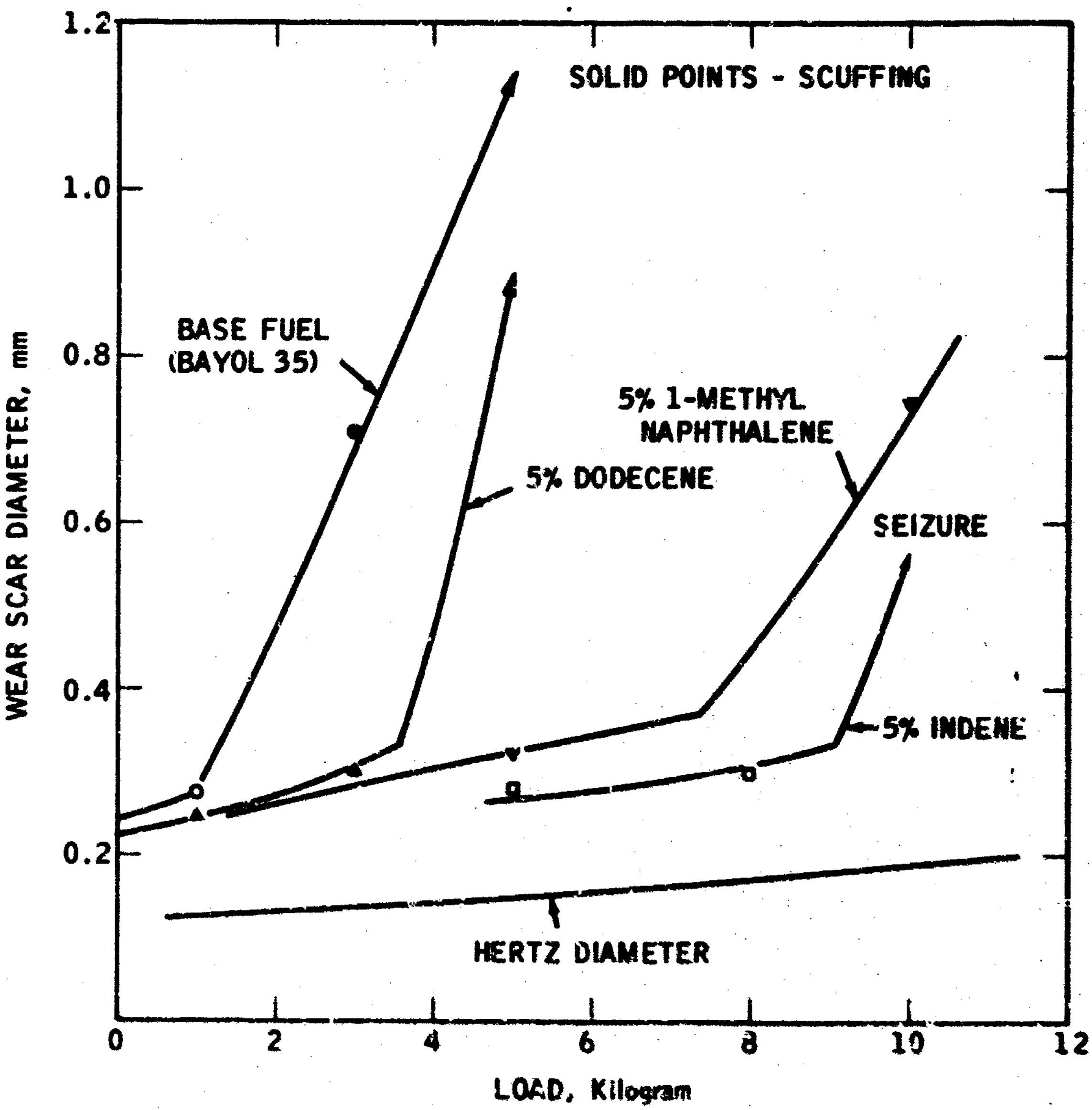


FIGURE 7 - EFFECT OF HYDROCARBON TYPE ON SCUFFING LOAD IN ARGON
(FOUR-BALL TESTS - 240F, 1200RPM, 52100 STEEL, 15 MIN.)

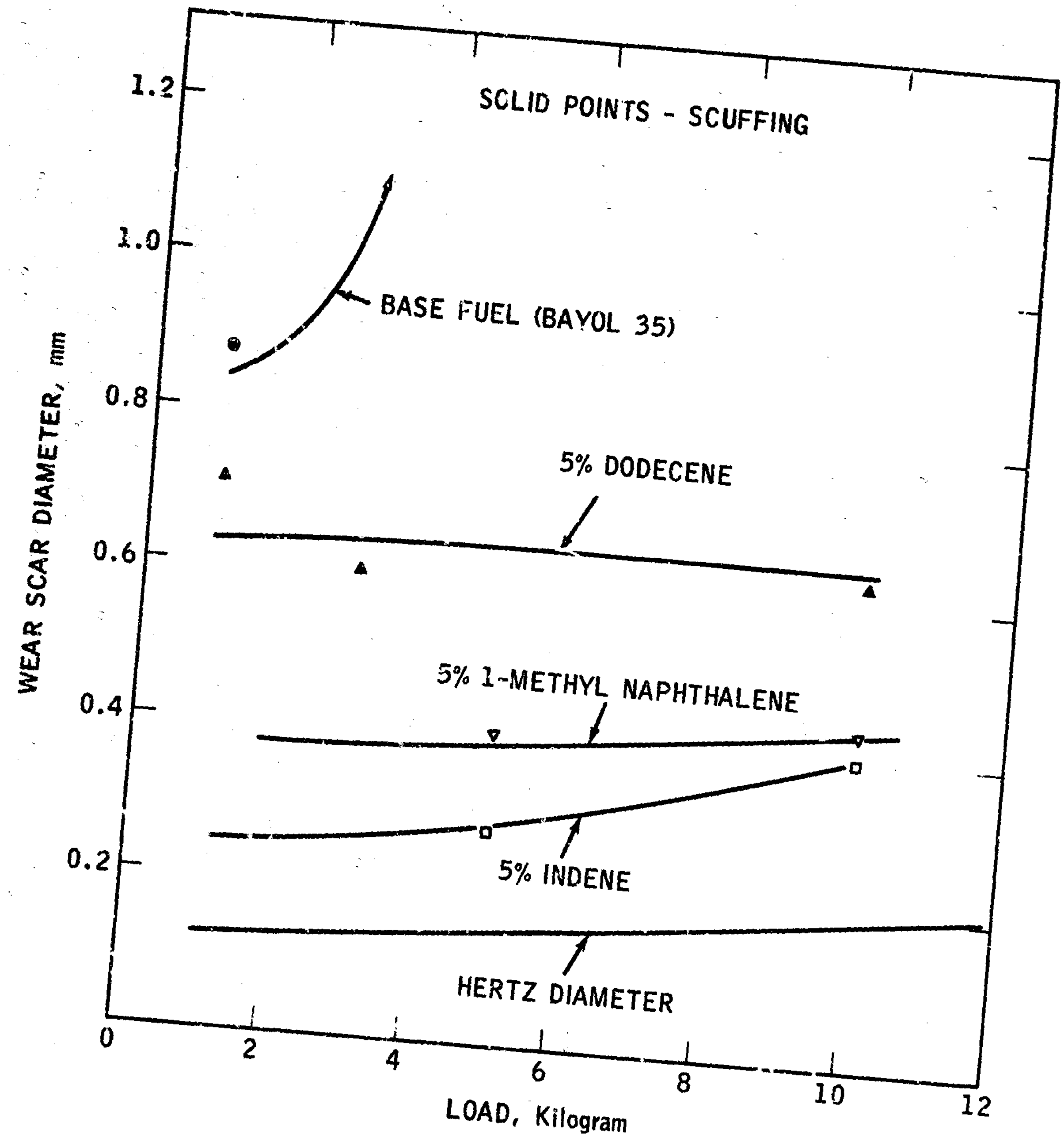


FIGURE 8 - EFFECT OF HYDROCARBON TYPE ON SCUFFING LOAD IN WET AIR
(FOUR-BALL TESTS - 240F, 1200RPM, 52100 STEEL, 15 MIN.)

TABLE 4

ATMOSPHERIC EFFECT ON SCUFFING LOAD

(Four-Ball Tests, 240F, 1200RPM, Steel-Steel)

Additives	Scuffing Load, kg In Argon	In Wet Air
1. Effect of Lubricity Additives:		
Base Fuel - FW-523	1	<0.5
50ppm ER-1	2	>10;<15
50ppm ER-3	5	>15
50ppm Oleic Acid	3	>15
50ppm ZnDDP	2	2
2. Effect of Hydrocarbons:		
Base Fuel - Bayol 35	3	<1
5% Dodecene	4	1
5% 1-Methylnaphthalene	10	>10
5% Indene	10	>10

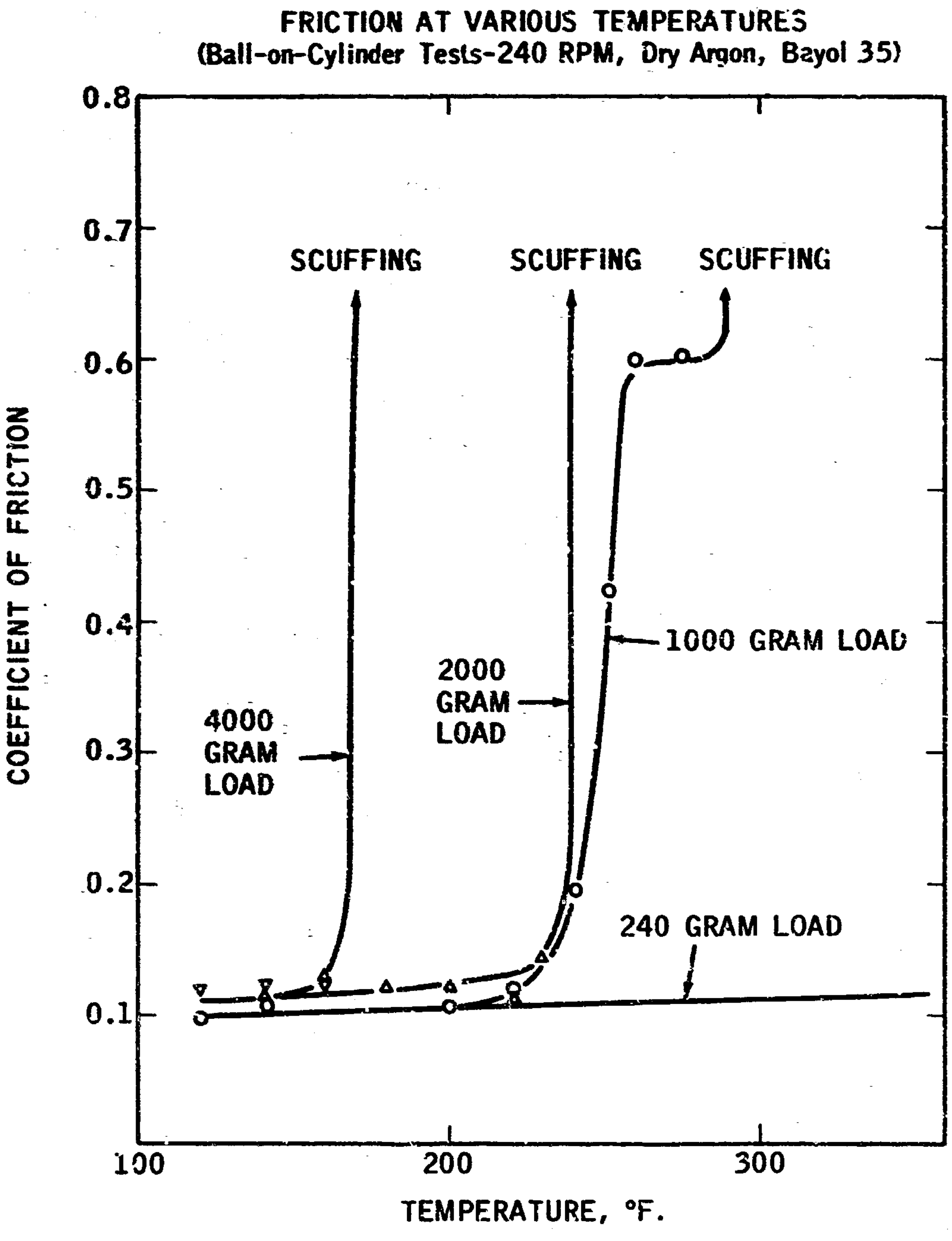


FIGURE 9 - FRICTION AT VARIOUS TEMPERATURES (BALL-ON-CYLINDER TESTS - 240RPM, DRY ARGON, BAYOL 35)

level before failure. Figure 10 is a photomicrograph showing the difference in the appearance of the wear scars. When failure had occurred, the wear scar showed welding and metal transfer. When the test was stopped before failure, there was no sign of welding or metal transfer.

A plot of scuff temperature vs. load (Figure 11) shows that scuff temperature decreases smoothly as load increases.

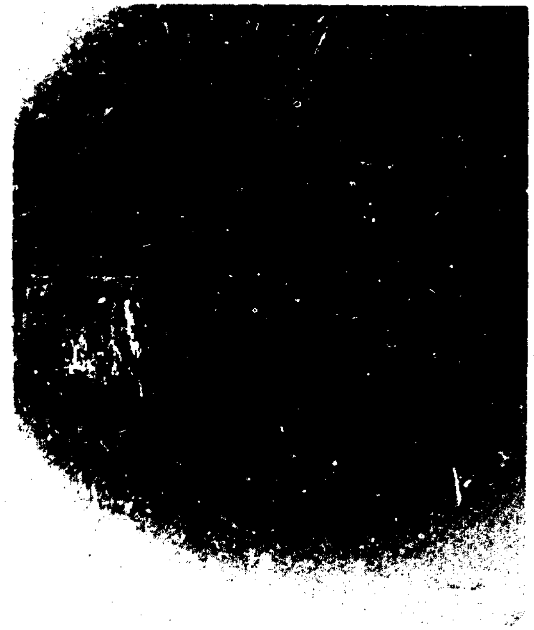
Additives were also tested in this manner, using a load of 4000g. Results are given in Table 5. Those additives that gave a higher scuff load in the four-ball tester also gave a higher scuff temperature in the ball-on-cylinder device. ER-3 was best, showing no failure. A photomicrograph of the wear scar from this run is also shown in Figure 10. The other additives were in the order oleic acid, ZnDDP, and ER-1. It is noteworthy that whereas ZnDDP and ER-1 showed no effect on scuff load in the 4-ball test, they did show some effect on scuff temperature. It may be that this procedure is more sensitive in picking up small differences, or it could be that this is due to a fundamental difference in the test procedures. In the scuff temperature test, the additive has a longer time to establish a protective film. This will be checked further.

Of the hydrocarbons, methylnaphthalene showed no failure, while dodecene was entirely ineffective.

Two sulfur compounds were also examined: 170ppm of thiophenol (50ppm as S) showed some effect, but 550ppm of butyldisulfide (200ppm as S) was as good as 50ppm oleic acid. Earlier data had shown that butyldisulfide was not effective in reucing wear at room temperature. This deserves further investigation.

In summary, the investigation of scuffing generally agrees with earlier data on wear. However, unlike wear, scuffing is frequently more severe in dry argon than in wet air. It appears that water vapor may increase wear but decrease scuffing. Another difference is that sulfur compounds, which were quite ineffective in reducing wear, showed some anti-scuff tendencies, at least at higher temperatures.

WEAR SCAR AT FAILURE
(290F)



WEAR SCAR AT HIGH FRICTION
(275F)

0.5mm

FOR 50PPM ER-3
(4KG LOAD, 350F)

FIGURE 10 - MICROGRAPH (88X) OF WEAR SCAR ON BALLS FROM SCUFFING TEMPERATURE TESTS
(BALL-ON-CYLINDER TESTS, 1000G, 240RPM, ARGON, BAYOL 35

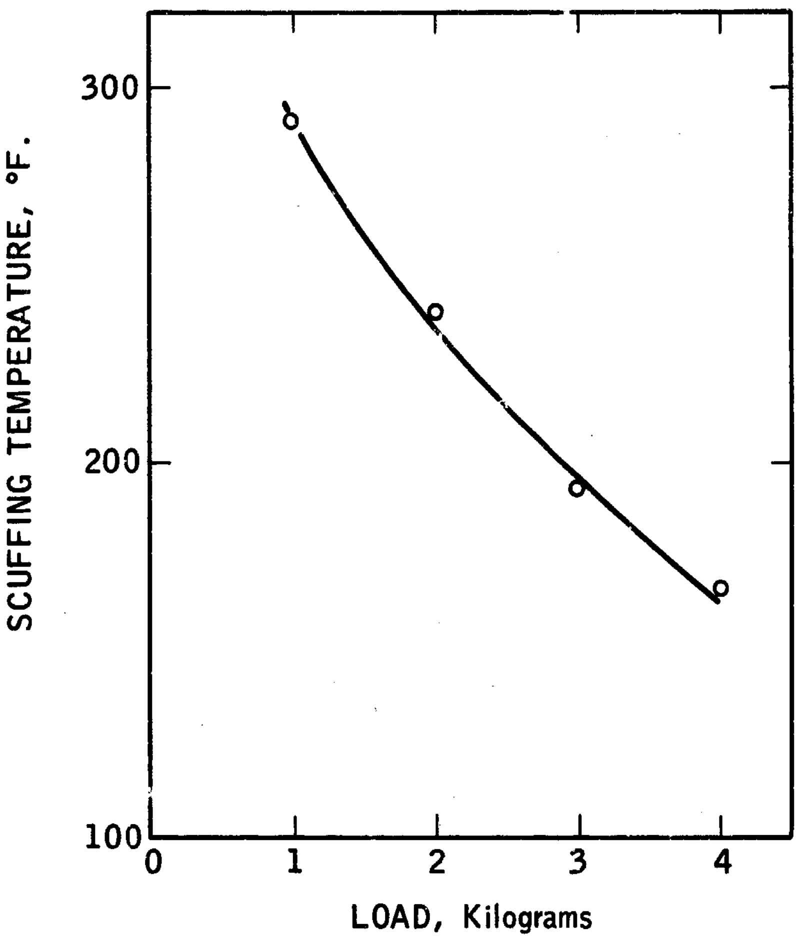


FIGURE 11 - SCUFFING TEMPERATURE VERSUS LOAD
(BALL-ON-CYLINDER TESTS - 240RPM, ARGON, BAYOL 35)

TABLE 5

ADDITIVE EFFECT ON SEIZURE TEMPERATURE

(Ball-on-Cylinder Tests--4000g, 240RPM, Argon, Steel-on-Steel)

Base Fuel: Bayol 35

Cylinder No.	Additive	Seizure Temperature °F.	Run Time Min.
136	None	177	5
	50ppm ZnDDP	280 (285)	14 (15)
	50ppm Oleic Acid	328	19
	50ppm ER-1	265	11
	50ppm ER-3	>350	27
137	None	160	3
	5% Dodecene	185	5
	5% 1-Methylnaphthalene	360	25
	5% Indene	310	22
140	None	195	5
	50ppm S as Thiophenol	252	13
	200ppm S as Butyldisulfide	330	18

IV. EFFECT OF VARIOUS METALLURGIES

During this program, it has been shown that mild corrosive wear, high corrosive wear, or severe scuffing can all occur, depending on operating conditions (e.g., load), fuel type, additives present, and atmosphere. It has also been shown that corrosive wear can lead to another form of wear, abrasive wear. It was felt that the role of metallurgy on the type and extent of wear that occurs could be important. Therefore, metals of varying degrees of corrosion resistance and hardness are being investigated. These include K-Monel, stainless steel-302, and gold in the form of gold-plated steel.

A. K-Monel

1. Four-Ball Tests With K-Monel

K-Monel was chosen as a metal to study because it is known to have very good resistance to corrosion. The Rockwell C hardness, R_C, of the K-Monel used for this work is 27. A typical composition of K-Monel is 66% nickel, 29% copper, and 3% aluminum.

Bayol 35 was tested at several loads using the four-ball tester with K-Monel balls. The results are shown in Table 6 and Figure 12. Several things may be seen from these results. First, with K-Monel, scuffing occurs very easily in dry argon. Even at 1 kg scuffing was always obtained. Previous tests with 52100 steel did not scuff in argon at these low loads. The effect is probably more than just the effect of a softer ball, since 52100 steel which had been softened to $25R_C$ did not scuff at 5kg in dry argon. Tests using K-Monel in wet air showed very small increases in wear scars with increasing load (Figure 12). Moreover, these wet air tests exhibited very smooth friction traces.

Photographs of the wear scars for 3kg are shown in Figure 13. These photographs illustrate the great difference between the type of surface damage with K-Monel when tested in dry argon and wet air atmospheres. This is very similar to the difference reported earlier between dry argon and wet argon when running with no lubricant in the ball-on-cylinder machine. The presence of water vapor prevents scuffing; the absence of corrosion with K-Monel gives a small wear scar.

For tests with K-Monel in wet air, the friction coefficient showed a slight decrease with increasing load, Figure 14. This is typical of non-scuffing friction.

The effect of an aromatic (1-methylnaphthalene) added to Bayol 35 is shown in Table 7 and Figure 15. As shown, scuffing occurs readily in dry argon. The observed scuffing was characterized by severe noise, high and erratic friction, and large wear scars (WSD usually greater than 2mm). The wear scars that occurred during scuffing tests appeared as in Figure 13(a). Synergism, similar to that found with chrome steel occurred near 30% 1-methylnaphthalene (see Figure 15). For wet air, low concentrations of 1-methylnaphthalene are no more effective in wear protection than Bayol 35 alone. With pure 1-methylnaphthalene, scuffing occurred in wet air as well as in dry argon. Apparently, wet air does not reduce the scuffing tendency for 1-methylnaphthalene with K-Monel as previously found for chrome steel.

Several fuel lubricity additives were tested in Bayol 35 to determine

TABLE 6

4-BALL TESTS: K-MONEL

(1200rpm, 15Min, Room Temperature, Bayol 35)

	Dry Argon		Wet Air	
Load, kg	Co Fr @ 15Min	WSD (mm)	Co Fr @ 15Min	WSD (mm)
1	0.77*	Scuff	0.16	0.51
2	0.51	Scuff	-	-
3	0.53**	Scuff	0.12	0.58
3 (Repeat)	0.57	Scuff	0.12	0.58
4	-	-	0.14	0.54
5	-	-	0.13	0.57
7	-	-	0.13	0.61
10	-	-	0.09	0.61

* Highest value.
** Ball slipped.

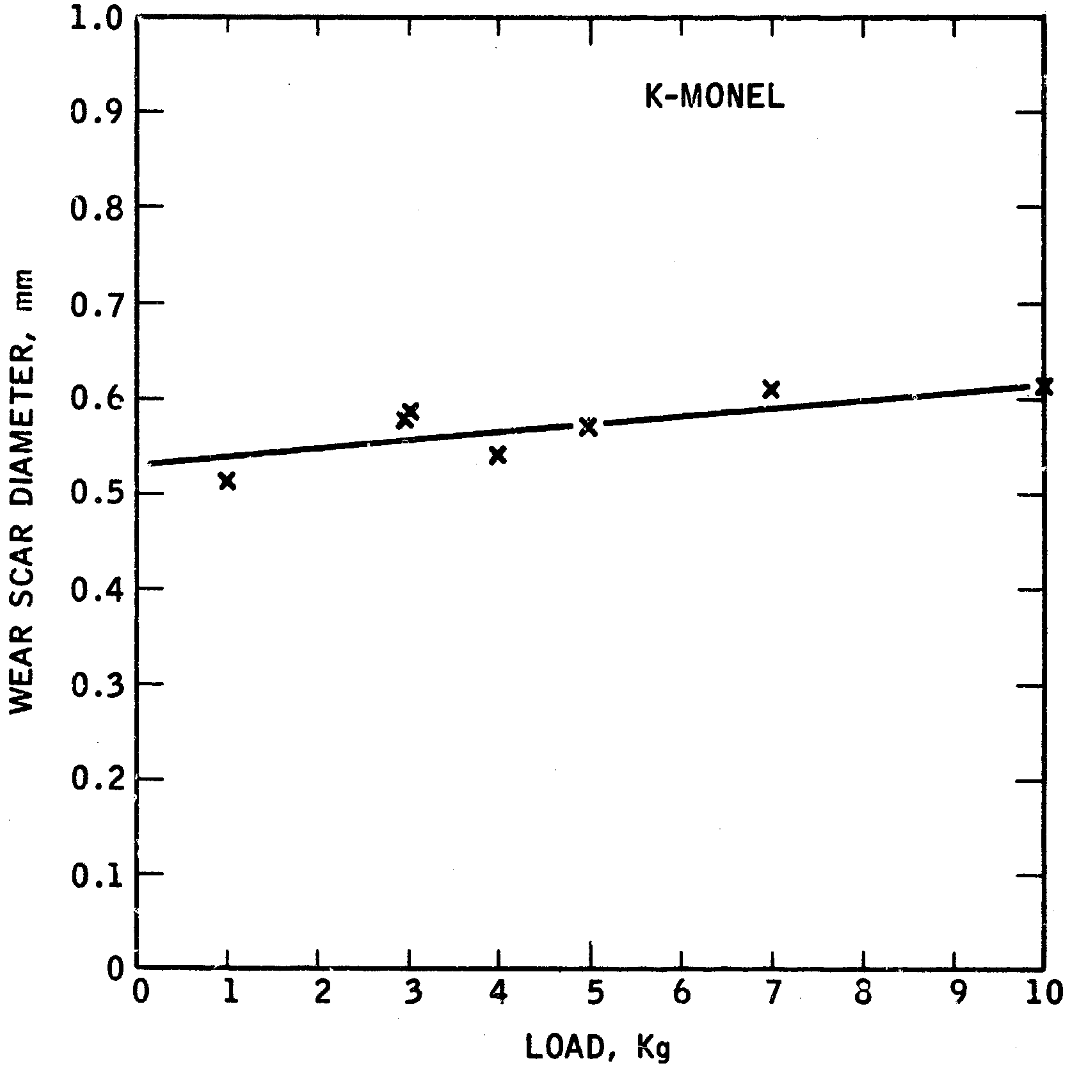
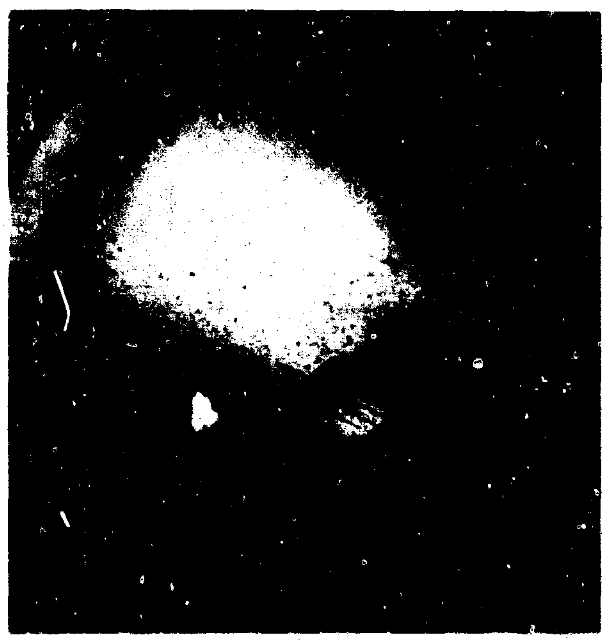


FIGURE 12 - EFFECT OF LOAD ON WEAR WITH K-MONEL (FOUR-BALL TESTS - 1200RPM, 15 MIN. 77F, BAYOL 35, WET AIR)

(a) DRY ARGON (3.5 Min.)



(b) WET AIR (15 Min.)

FIGURE 13 - PHOTOMICROGRAPHS OF WEAR SCAR
(FOUR BALL TESTS - 1200RPM, K-MONEL,
BAYOL 35, ROOM TEMP., 3KG)

1.01 mm

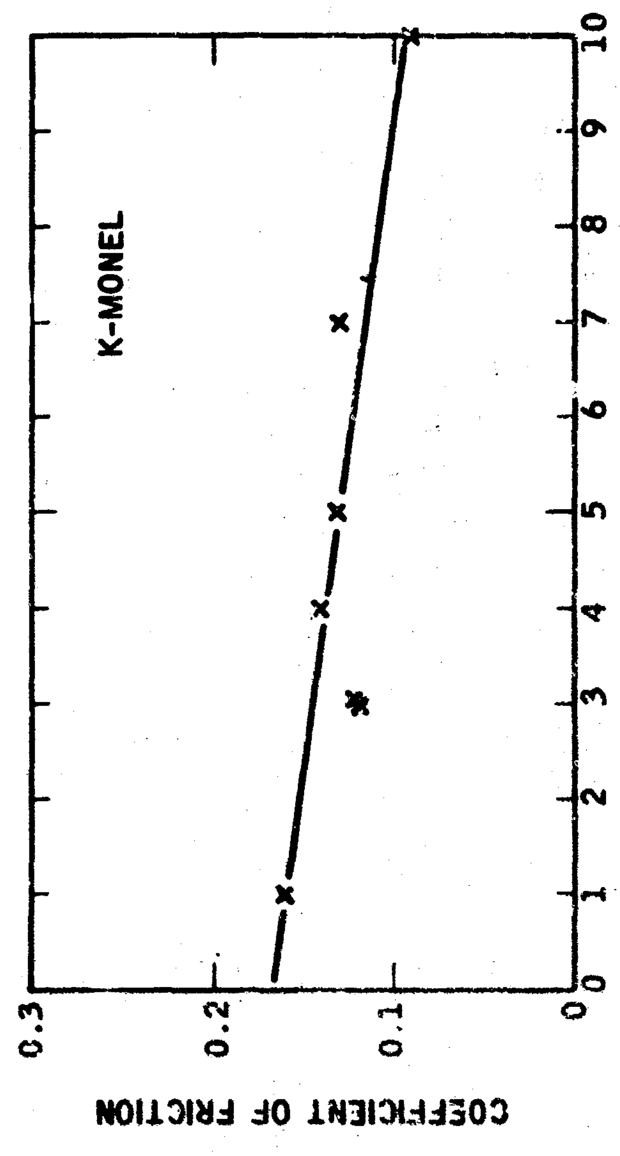


FIGURE 14 - EFFECT OF LOAD ON FRICTION WITH K-MONEL (FOUR-BALL TESTS - 1200RPM, 15 MIN. 77F, BAYOL 35, WET AIR

TABLE 7

EFFECT OF 1-METHYLNAPHTHALENE WITH K-MONEL

(1200rpm, 15Min, 3kg, 77F)

Wt% 1-Methylnaphthalene In Bayol 35	Dry Argon Co Fr @ 15Min	Dry Argon WSD (mm)	Wet Air Co Fr @ 15Min	Wet Air WSD (mm)
None	0.57	Scuff	0.12	0.58
5	Off Scale	Scuff	0.14	0.51
15	0.34	Scuff	0.14	0.63
30	0.08	0.44	0.08	0.53
100 (1-Methylnaphthalene)	0.81	Scuff	0.48	Scuff

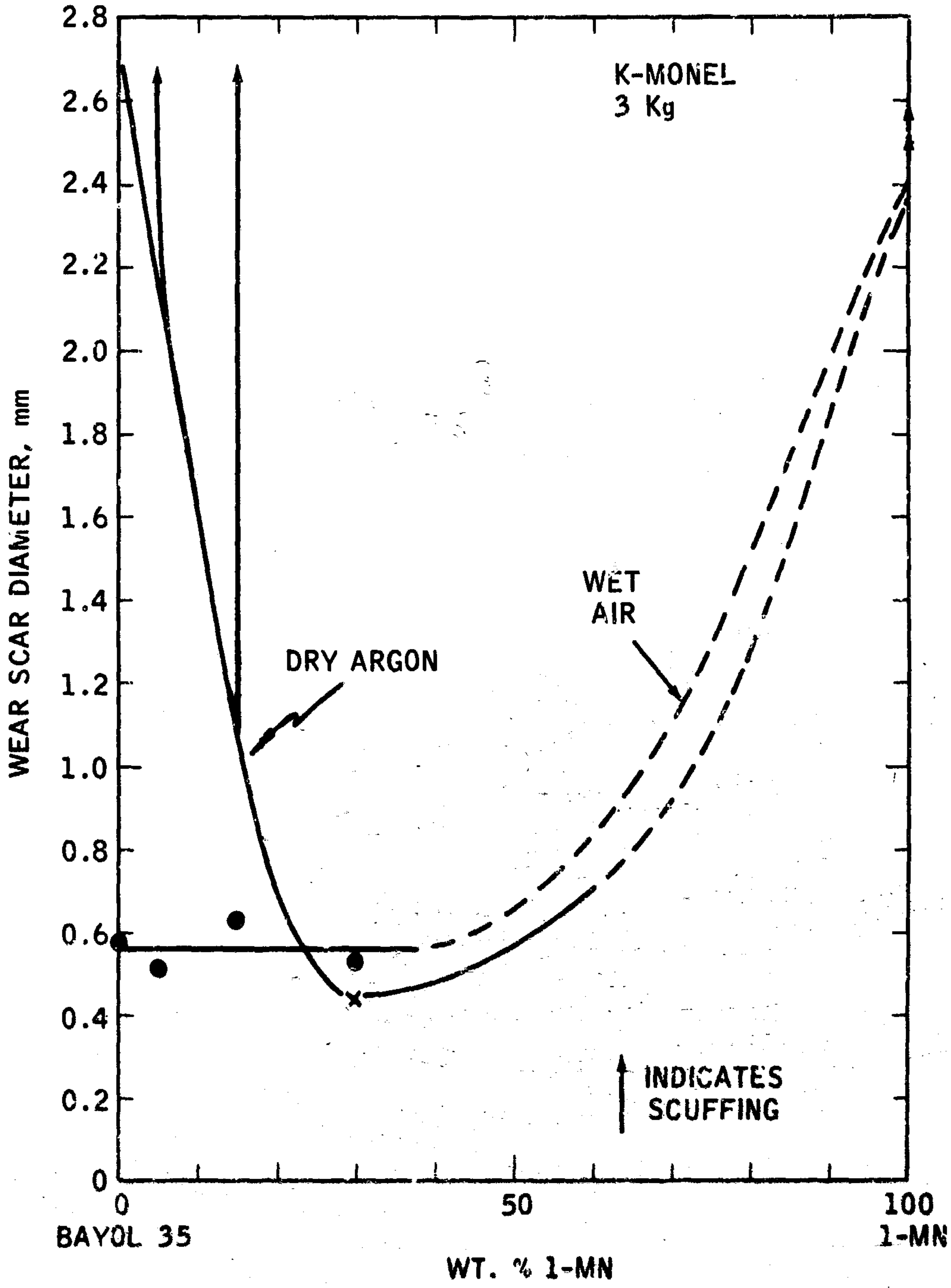


FIGURE 15 - EFFECT OF 1-METHYLNAPHTHALENE CONCENTRATION ON WEAR (1200RPM, 15MIN, ROOM TEMP, FOUR-BALL TESTS)

their effectiveness on K-Monel. Results at 3kg load are shown in Figure 16. Included also in Figure 16 are values from tests with Bayol 35 plus 30% 1-methylnaphthalene. As may be seen from Figure 16, in dry argon ER-3 was the only additive (excluding 1-methylnaphthalene) which eliminated scuffing. The amount of wear that occurred in dry argon with ER-3 was practically identical to that obtained with 30% 1-methylnaphthalene. In wet air, none of the additives tested were effective in reducing the wear level of Bayol 35 alone. Oleic acid, to the contrary, acted as a pro-scuff agent in wet air. The test was repeated, and again scuffed. A new solution of oleic acid in Bayol 35 was then made and again scuffing occurred. The reason for the pro-scuffing characteristics of oleic acid in wet air is not known at this time. Additional work is being done.

Oleic acid and ER-3 were also tested at 1 kg load. Results are shown in Figure 17. As may be seen, oleic acid scuffs in dry argon as does the base fluid, Bayol 35. However, now at the lower load, oleic acid does not act as a pro-scuff agent in wet air. As before, ER-3 is effective is controlling scuffing in dry argon, but neither oleic acid nor ER-3 lowers the wear of Bayol 35 in wet air.

Friction data for the additive tests are shown in Table 8. In most cases, when scuffing occurred, the friction coefficient was high or off-scale. One test with oleic acid showed high friction throughout most of the test but dropped in friction for the last few minutes.

To summarize, K-Monel is easily scuffed in dry argon; loads as low as 1 kg are too high. Wet air prevents scuffing with Bayol 35 but not with 1-methylnaphthalene. A solution of 30% 1-methylnaphthalene shows synergism in dry argon - scuffing is prevented. Concerning additives, ER-3 prevents scuffing in dry argon; the others are ineffective. In wet air, none of the additives, except oleic acid, has any effect on wear compared to Bayol 35 alone. Oleic acid, however, apparently acts as a pro-scuff agent at 3kg in wet air.

2. Ball-On-Cylinder Tests

Several ball-on-cylinder tests were run using K-Monel balls on a 52100 steel cylinder. Test conditions were: 240rpm, 240g load, 160F, in both dry argon and wet air. Bayol 35 was used as the test fuel. In both cases, the tests had to be discontinued in less than 3 minutes due to excessive chatter. Friction was wild and off-scale, and metallic contact was 100%.

As mentioned earlier, K-Monel contains nickel, copper, and aluminum. All three of these metals are miscible with steel. Both nickel and aluminum are known to have very poor scuff resistance when in combination with steel whereas copper against steel has only a fair scuff resistance.* However, steel-on-steel, a completely miscible system, is satisfactory under these test conditions. Thus, the use of easily scuffed dissimilar metals is not the answer here. The low chemical reactivity of K-Monel or its relative softness may be the cause of its poor ball-on-cylinder performance.

* Coffin, Jr., L. F., Proc. Sym. Frict. and Wear, Robert Davies, Ed., p. 36, Elsevier, N.Y. (1959); see also Goodzeit, C. L., Ibid., p. 67.

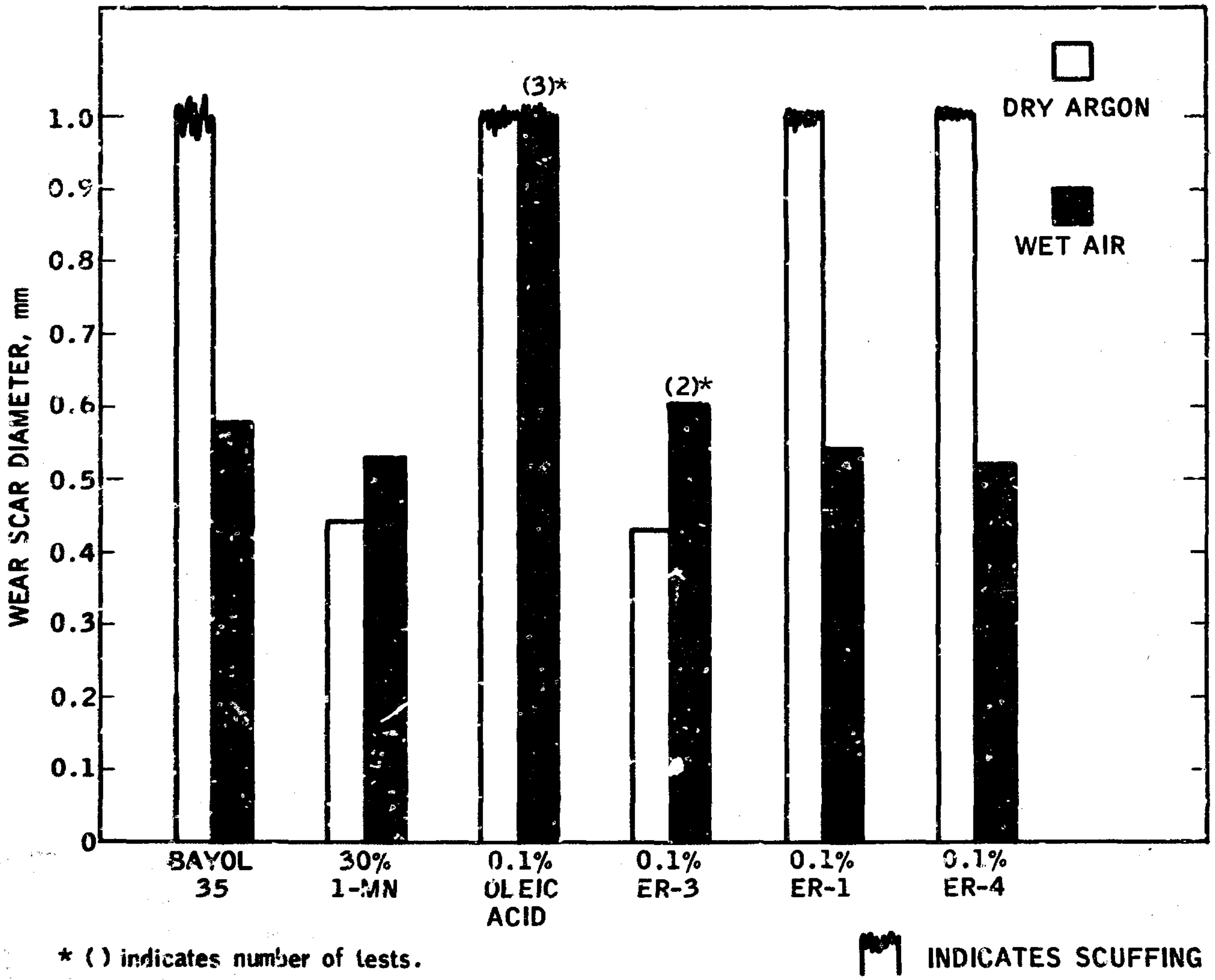
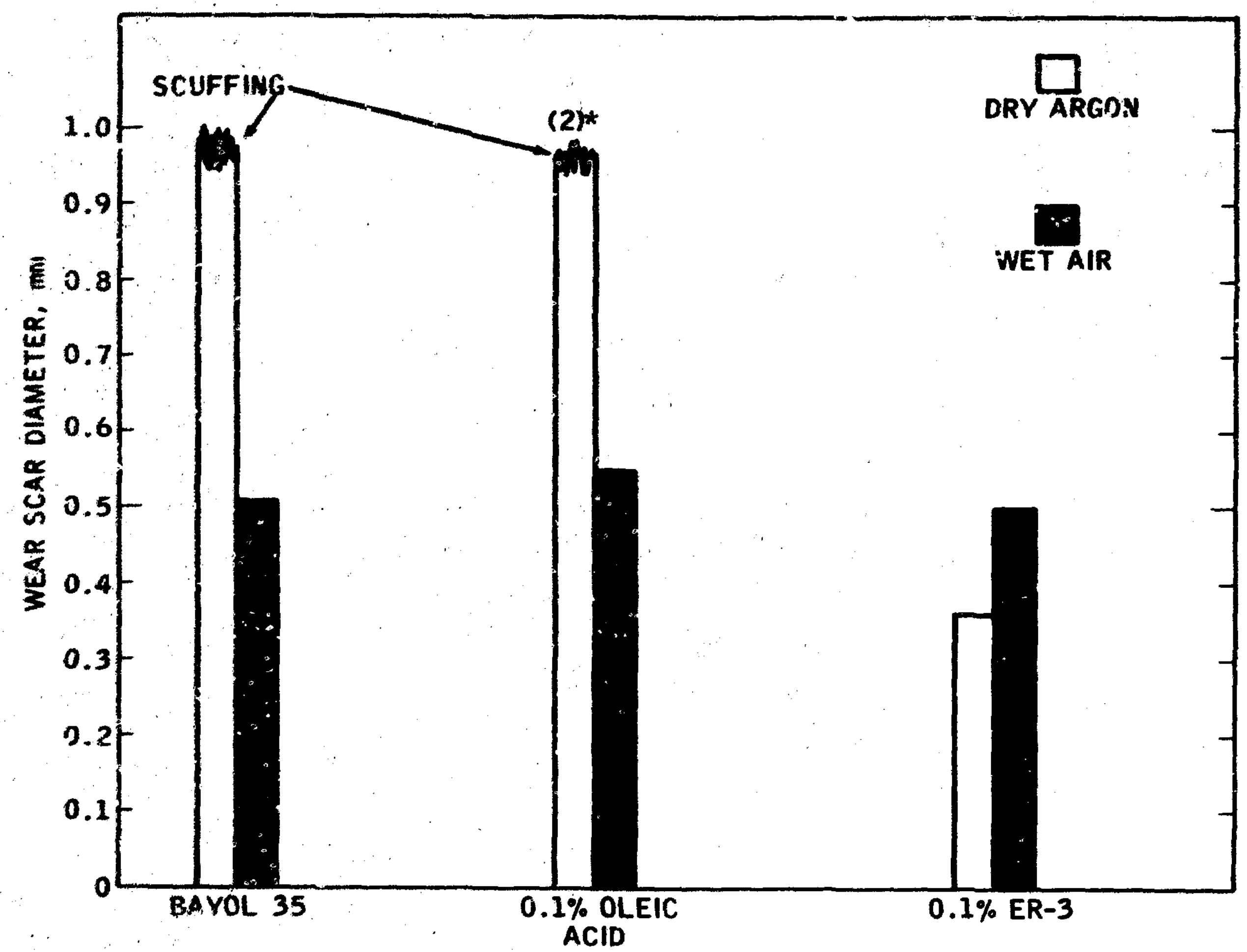


FIGURE 16 - EFFECT OF ADDITIVES ON K-MONEL (3KG)
FOUR-BALL TESTS (1200RPM, 15 MIN., 77F TEMP.)



* ( ) indicates number of tests.

FIGURE 17 - EFFECT OF ADDITIVES ON K-MONEL (FOUR-BALL TESTS, 1200RPM, 15 MIN., 77F TEMP., 1 KG)

TABLE 8

FRICTION SHOWN BY ADDITIVES WITH K-MONEL

(1200rpm, 15Min, 77F)

Wt% Additive In Bayol 35	Coefficient of Friction(@ 15Min)			
	Dry Argon		Wet Air	
	1 kg	3kg	1 kg	3kg
None	0.77*	0.57	0.16	0.12
0.1 Oleic Acid	0.60	Off Scale	0.09	0.06**
0.1 Oleic Acid	0.65	-	-	0.22
0.1 ER-3	0.16	0.13	0.14	0.14
0.1 ER-3	-	-	-	0.12
0.1 ER-1	-	Off Scale	-	0.10
0.1 ER-4	-	Off Scale	-	0.10

* Highest value.
** Friction coefficient was erratic at level of 0.3 to 0.9 for first 11 min, then dropped to 0.06.

B. Stainless Steel - Type 302

Tests were run using the four-ball tester with 302 stainless steel. This metal is more corrosion resistant than the previously-tested SS-440C. Thus it more nearly resembles K-Monel.

The results at 1 and 3kg are shown in Table 9. Of all the tests at 3kg only 1-methylnaphthalene does not scuff (wet air). Under the same conditions, scuffing occurred with 1-methylnaphthalene on K-Monel. With SS-302, 1-methylnaphthalene shows much better performance in wet air than in dry argon (Table 9). With K-Monel, there was no difference in performance between the two atmospheres with 1-methylnaphthalene. The difference between K-Monel and SS-302 with 1-methylnaphthalene cannot be fully explained at this time. Apparently, SS-302 is behaving more like a steel than like a non-corrodible metal such as K-Monel.

Figure 18 shows the effect of 1-methylnaphthalene concentration on the wear of SS-302 for 1 kg load. As previously found for other metallurgies, synergism is seen at 30% 1-methylnaphthalene in dry argon. In wet air, 1-methylnaphthalene is better than both Bayol 35 and Bayol 35 with 30% 1-methylnaphthalene (see also Table 9).

Summarizing, data with SS-302 illustrate the importance of moisture and/or oxygen in the atmosphere during the wear test. Additional data in wet argon and dry air are being obtained to determine which factor is the more important one. Under the present conditions, the four-ball test is too severe even at 1 kg for evaluating Bayol 35 with SS-302 under non-scuffing conditions. This is also true for K-Monel in dry argon. Operating at lower speeds may reduce the scuffing tendency since lower sliding temperatures would be reached.

C. Gold On Gold

Gold was chosen to study because of its high resistance to corrosion. Thermodynamics considerations indicate that gold does not normally form oxides (the free energy of formation of gold oxides is +10.5kcal per oxygen atom). The following work was carried out using steel balls electrolytically coated with gold, the gold plating being 1/10,000 inch thick.

1. Four-Ball Tests

Because of the extremely thin coating of gold, it was found that the 4-ball machine was too severe, even at the lightest attainable load of 1 kg. Over a range of light loads (1-5kg) the gold coating was broken through, as evidenced by the nature of the friction trace and microscopic examination of the wear area. A typical friction trace exhibiting breakthrough of the gold coat is shown in Figure 19. The gold coat appears to have broken-through at 3.5 minutes.

With a noble metal such as gold, no corrosive wear would be expected to occur. However, an increase in wear scar was observed in going from dry argon to wet air, as shown below:

	Dry Argon	Wet Air
WSD, mm	0.25	0.37

Conditions: 1200rpm, 1 kg, 77F, Bayol 35

TABLE 9

4-BALL STUDIES WITH STAINLESS STEEL 302

(1200rpm, 15Min, 77F)

Wt% 1-Methylnaphthalene In Bayol 35	Coefficient of Friction @ 15Min			
	Dry Argon		Wet Air	
	1 kg	3kg	1 kg	3kg
None	Off Scale	0.47*	Off Scale	0.36*
None**	Off Scale	-	Off Scale	-
30	0.25	Off Scale	0.23	0.44*
100	0.16	0.39	0.08	0.02

	Wear Scar Diameter, mm			
	Dry Argon		Wet Air	
	1 kg	3kg	1 kg	3kg
None	Scuff	Scuff	Scuff	Scuff
None**	Scuff	-	Scuff	-
30	0.24	Scuff	0.30	Scuff
100	0.22	Scuff	0.24	0.33

* Friction trace erratic.

** Repeat test.

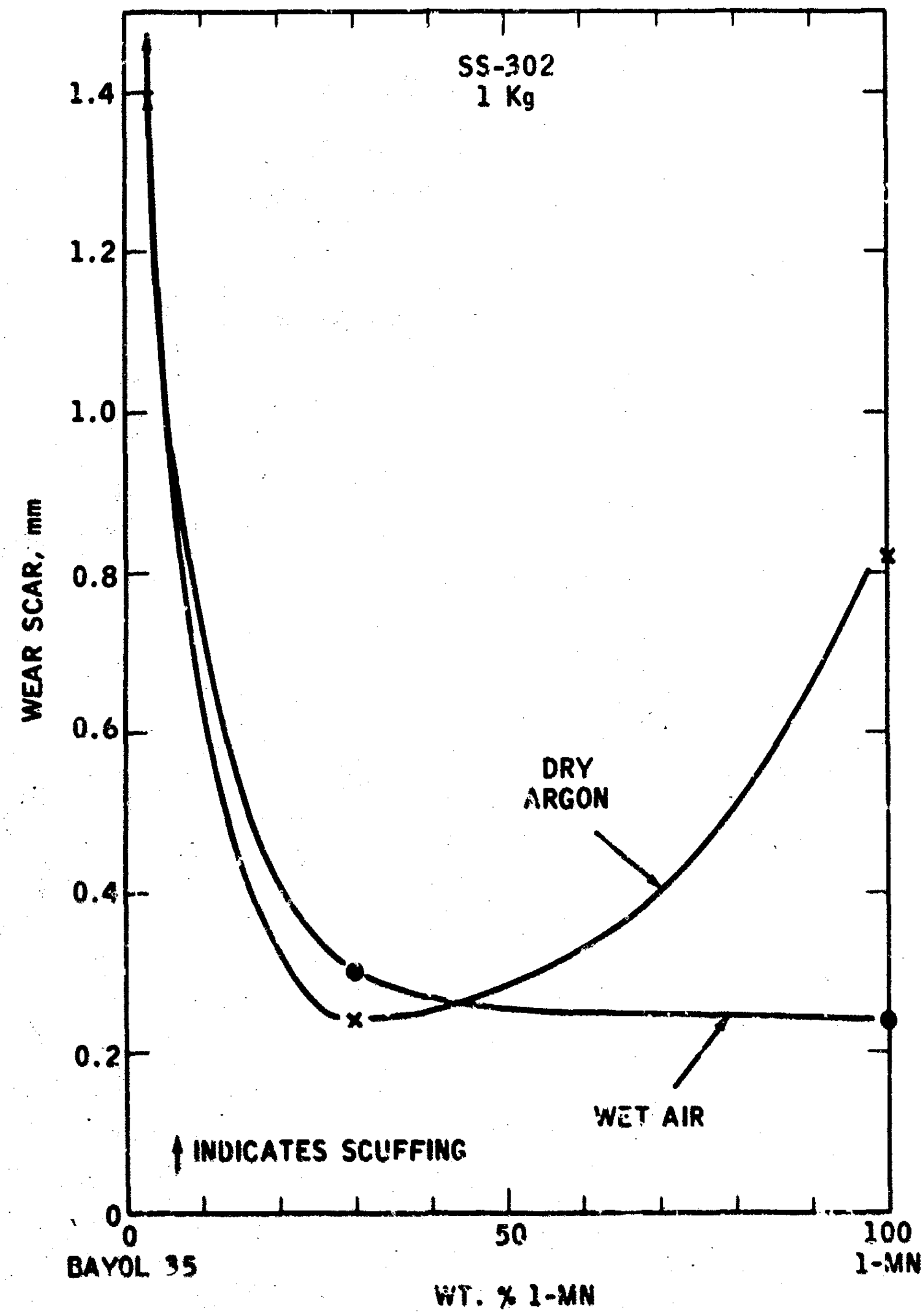


FIGURE 18 - EFFECT OF 1-METHYLNAPHTHALENE ON WEAR OF SS-302 (FOUR-BALL TEST - 1200RPM, 77F)

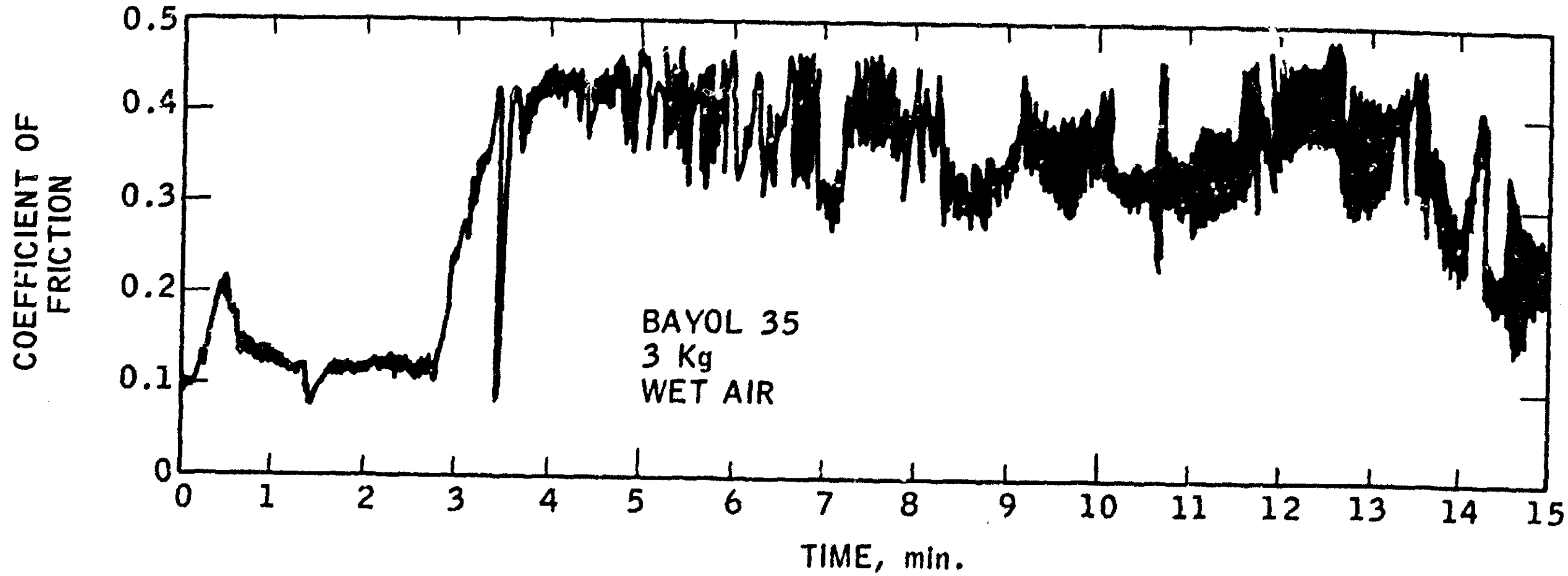


FIGURE 19 - EXAMPLE OF FRICTION TRACE OBTAINED WITH GOLD-PLATED STEEL BALLS (FOUR-BALL TEST - 1200RPM, 15 MIN. 97F)

Thus, wear of the steel substrate is occurring, another indication that the gold coating has broken through.

2. Ball-On-Cylinder Tests

Because of the difficulties encountered testing gold-plated balls on the 4-ball machine, additional tests were carried out under much lighter loads using the ball-on-cylinder device. For these tests, a gold-plated ball was loaded against a gold-plated cylinder. The results at 20g load are shown in Table 10 along with data obtained at 100g. At 20g, it can be seen that the atmosphere has no effect on the wear scars. This is in contrast to steel-on-steel where higher wear was obtained in wet air. Microscopic examination of the wear areas showed that the gold coat had not been broken through in these 20g tests. The friction trace also showed no signs of tearing through the gold-plate. This is illustrated in Figure 20 for dry argon.

At 100g load and 180F, atmosphere has very little effect on the wear scars (see Table 10). The friction traces and examination of wear areas again indicated that the gold had not been broken through. Several tests were also run at 100g load but at 250F. At this temperature, the test was apparently more severe than at 180F as the gold-coating was broken through.

To summarize, at very low loads, far below those required for scuffing of steel surfaces, no difference between dry argon and wet air was observed in the wear characteristics of gold. That is, no corrosive wear occurred with gold as did with steel surfaces. Because of the difficulties encountered using the gold-plated balls at higher loads, no further work is anticipated with the gold-on-gold system. In the future, metals will be used which either have very durable coatings or consist of a single metallurgy entirely.

D. Comparison Of Various Metallurgies Studied

A comparison of several metals, all run with Bayol 35 as the fuel, is shown in Table 11. As a first attempt to find a property which might be used to correlate the wear performance of the various metals, Brinell Hardness, the elasticity (E), and the hardness to elasticity ratio (H/E) is also tabulated. As may be seen in the table, the difference in the wear characteristics of the various metallurgies may not be attributed to any of these mechanical properties of the metals. For example, K-Monel and the softened 52100 steel with roughly the same hardness performed vastly different in dry argon. Again, K-Monel and stainless steel 302, having the same hardness to elasticity ratio, have very different wear performance in wet air. Apparently, as may be seen from the table, metals which are both soft and corrosion resistant scuff very easily, especially in dry argon. The reason is unknown at this time, and additional work must be done.

Another comparison of several metallurgies is shown in Figure 21 where gold-coated steel is compared to steel and stainless steel 440C, all in wet air. Note that at low loads the gold and the 440C both show less wear than the 52100 steel. With increasing load, the gold and the 52100 steel show higher wear levels than the stainless steel 440C. This is probably due to lower corrosion resistance of the 52100 steel as compared to the stainless steel 440C. At the higher loads the gold coating has been broken through, and the gold system behaves very much like the 52100 steel system.

TABLE 10

BALL-ON-CYLINDER TESTS: GOLD-ON-GOLD

(32Min, 240rpm, 180F, Bayol 35)

Load (grams)	Dry Argon Co Fr @ 32Min	Dry Argon WSD (mm)	Wet Air Co Fr @ 32Min	Wet Air WSD (mm)
20	0.83	0.40	0.63	0.42
100	0.49, 0.71	0.40, 0.40	0.37	0.46

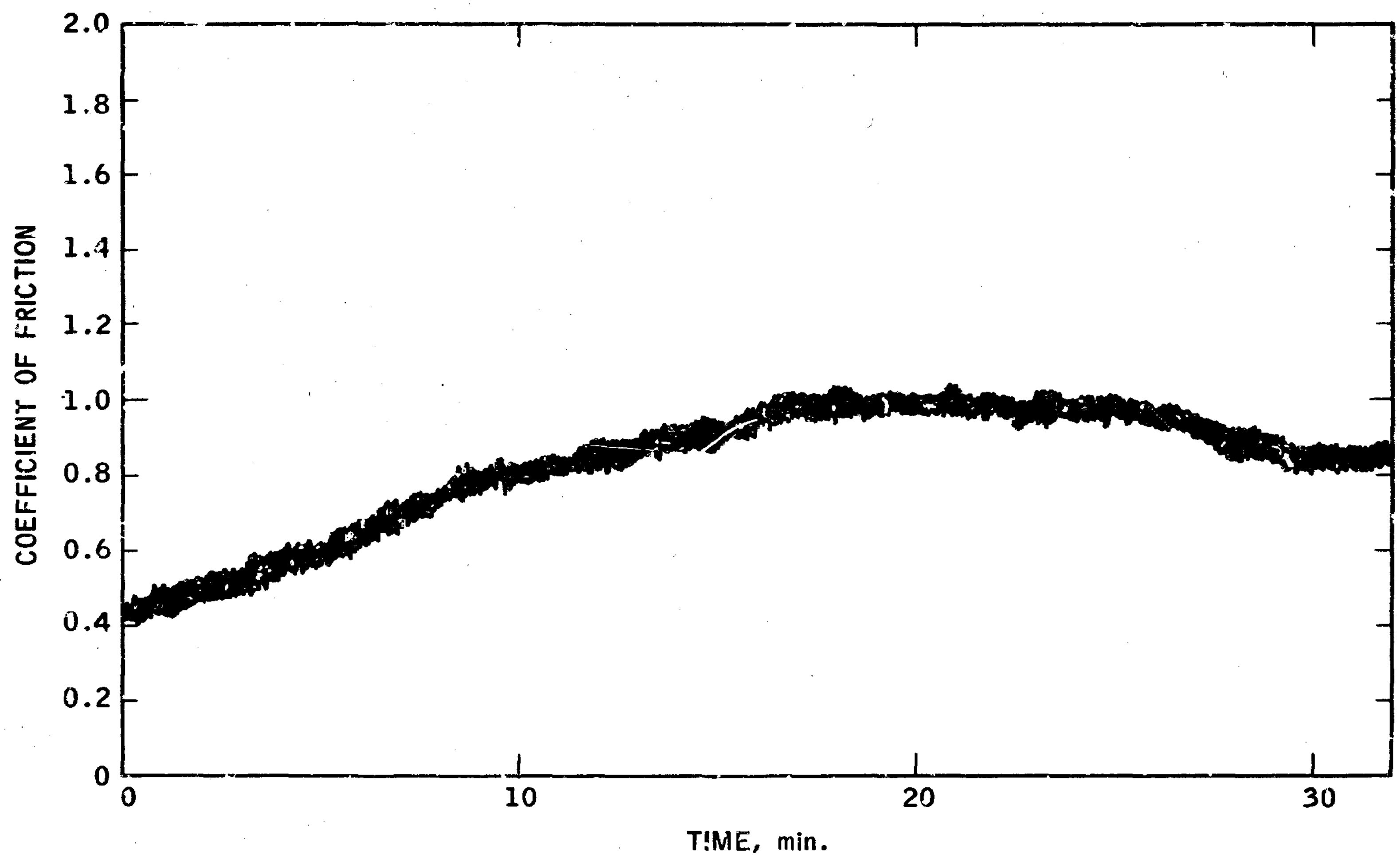


FIGURE 20 - FRICTION TRACE FOR GOLD-ON-GOLD (BALL-ON-CYLINDER TEST, 240RPM, 20G, DRY ARGON, 180F, BAYOL 35)

TABLE 11

COMPARISON OF VARIOUS METALLURGIES IN 4-BALL TEST

(1200rpm, 15Min, 77F, 5kg)

Lubricant: Bayol 35

Metal	Brinell Hardness H	Elasticity, E psi x 10^{-6}	Brinell Hardness-Elasticity Ratio, H/E x 10^6	Wear Scar Diam (mm) Dry Argon	Wet Air
WC	1800	81	22	0.13	0.13
52100	600	29	21	0.28	0.63
SS-440C	600	29	21	0.21	0.31
SS-302	290	29	10	Scuff	Scuff
K-Monel	260	26	10	Scuff	0.57
52100	261	29	9	0.30	0.47

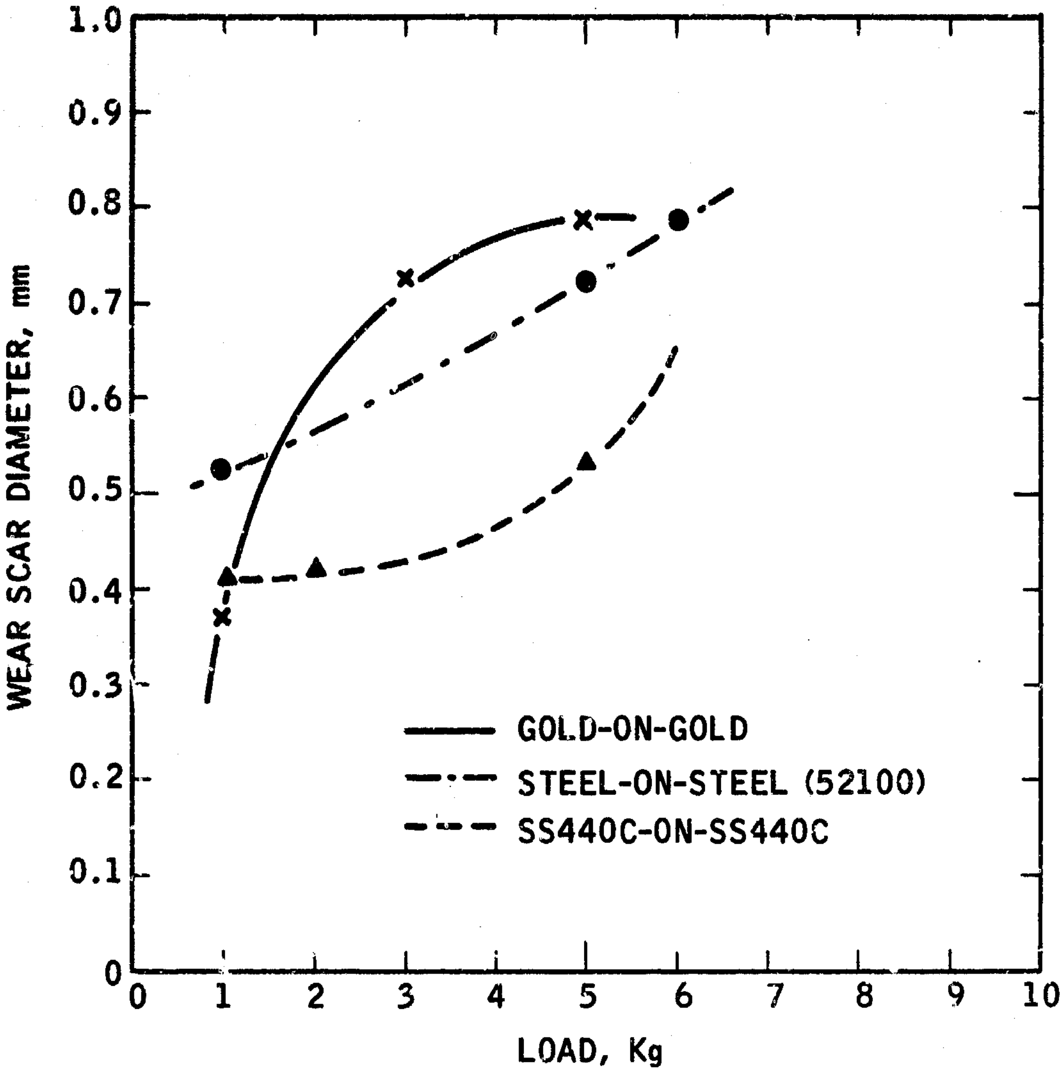


FIGURE 21 - COMPARISON OF SEVERAL METALLURGIES (FOUR-BALL TEST - 1200RPM, 15 MIN. WET AIR, BAYOL 35)

V. ABRASIVE WEAR

A third important mode of wear is by abrasion. This can be of two kinds: (1) If the surfaces are rough, the asperities of one surface can plow or scratch the other surface, (2) If hard particles (dirt or wear debris) are suspended in the liquid, they can become entrapped between the rubbing surfaces and cause scratching. This latter kind is of most interest here. It is particularly critical if the surfaces are case-hardened, for then the initial wear will result in very hard wear particles.

Abrasive wear, like scuffing, is sensitive to other kinds of wear occurring. For example, if corrosive wear takes place, the oxide wear particles can cause abrasion. It will be shown that this is indeed a critical factor in our work. It is also probable that abrasive wear can influence other kinds of wear. For example, abrasive wear will cut through the protective oxide film on the surface, exposing fresh metal. If enough fresh surface is exposed, scuffing can occur. In fact, this appears to be the mechanism of scuffing in wet air: corrosion causes abrasion,which causes scuffing.

A short program has been carried out in the Vickers vane pump to learn more about abrasive wear with jet fuels. From this work, the following conclusions can be drawn:

- There is further evidence that corrosive wear triggers abrasive wear.
- The increase in wear with increasing load is largely due to an increase in abrasive wear.
- The amount of abrasive wear is not linearly dependent on the amount of wear particles present, but requires a certain minimum amount before wear becomes serious.
- Abrasive wear could not be correlated with Moh hardness, crystal structure or particle size of several metal oxides.
- Unexpectedly, abrasive wear can be controlled by additives.

Previous data had shown that the wear debris from the Vickers pump test consisted of both iron and iron oxide. The iron oxide is believed to be from corrosive wear; that is, the oxidation occurred at the metal surface and the oxide particle was then worn off, rather than the reverse, the oxidation occurring after an iron particle was worn away. The amount of unoxidized iron is then a measure of the amount of abrasive wear.

A. Abrasive Wear Increases with Load

Two pump tests were run at different loads (different outlet pressures). The wear debris was analyzed for Fe°, Fe^{++}, and Fe^{+++}, as well as for O, C, and H. From this and the total weight loss, the amount of abrasive wear can be calculated. Table 12 presents the data. Raising the load from 250psig to 350psig increased wear from 3.2g to 6.1g. All of this increase was due to abrasive wear, the corresponding values being 2.2 and [illegible].9g. The amount of corrosive wear was almost exactly the same in the two cases: 1.47 and 1.43g as iron oxides.

TABLE 12

EFFECT OF LOAD ON ABRASIVE WEAR

(Vickers Vane Pump Tests - 90F, Room Air)

Pump Pressure, psig	250		350	
Ring Wear, mg	3122		5951	
Vane Wear, mg	125		171	
Total Wear, mg	3247		6122	
Analyses of Wear Debris, wt%				
Fe°	53.9		71.8	
Fe^{+2}	11.7	36.3	7.5	21.0
Fe^{+3}	11.3		6.8	
Oxygen	13.3		6.7	
C	5.4		7.6	
H	0.4		0.6	
Estimated Wear Debris*, mg	4055		6810	
Fe° in Wear Debris, mg	2190		4890	
Fe - Oxides in Wear Debris	1473		1430	

$$* = \frac{\text{(Total pump wear) (\% Fe in steel)}}{\text{\% Total Fe in Wear Debris}}$$

This conclusion is entirely logical. It means that corrosion occurs irrespective of load, but that abrasion is load-dependent.

B. Abrasive Wear Does Not Occur Until the Amount of Wear Debris Passes A Threshold Value

It is obvious that abrasive wear will not occur unless corrosive wear precedes it, for in the absence of oxygen no pump wear occurs at all. This makes it possible to test the abrasiveness of wear particles, uncomplicated by corrosive wear. Accordingly, the effect of particle concentration was evaluated in a series of tests on Bayol 35 in a nitrogen atmosphere. New Bayol 35 was mixed with varying amounts of Bayol 35 from an earlier test run in air at 250psig. The amount of wear debris was 0, 25%, 50% and 100% (100% equals 1.6mg debris per gram of fuel). The 100% test (no dilution with fresh fuel) was run by first running in air at 200psig and then in nitrogen using a new pump cartridge.

The data are given in Table 13. As expected, the fuels containing large amounts of wear debris gave very severe wear: 13.3g for the fuel containing all the wear debris from the preceding test, 11.7g for the fuel containing 50% of the debris. Surprisingly, however, the fuel with 25% of the debris showed almost no wear at all. Thus, abrasive wear is not a linear function of the amount of wear particles, but is in the form of Figure 23.

Analysis of the wear debris from the high wear tests shows that very little of it is iron oxide, thereby confirming that this is pure abrasive wear. Table 14 shows that the run containing 50% added wear debris started with 736mg iron oxide in the fuel and finished with 553mg. The entire 11,775mg wear was thus unoxidized iron.

C. Abrasive Characteristics of Iron Oxides Are Not Correlated with Hardness, Crystal Structure or Particle Size

Several different iron oxides and other metal oxides were obtained and tested for abrasive wear in the Vickers pump. They were added to Bayol 35 at 100ppm, which should be enough to cause abrasive wear, based on earlier tests. The results are given in Table 15. Both of the ferric oxides, α-Fe_2O_3 and γ-Fe_2O_3, gave severe wear, the weight loss being about 8 grams. Alundum (α-Al_2O_3) gave about 0.25g. The other three oxides--Fe_3O_4, FeO(OH) and Cu_2O--gave less than 50mg wear. FeO(OH) did give severe wear when the amount was increased to 320ppm, as shown in Table 16, another indication that abrasive wear is concentration-dependent. However, Fe_3O_4 gave no wear, even at 1000ppm.

It was rather surprising that no correlation could be found between abrasiveness and other properties such as hardness, particle size or crystal structure. Aluminum oxide is easily the hardest, yet it was not as abrasive as ferric oxide. Its particle size, by microscopic examination, was only slightly smaller. These data are also given in Table 16.

D. Oleic Acid Reduces Abrasive Wear

It has generally been assumed that additives such as oleic acid function as antiwear agents by chemisorbing on the surface, thus inhibiting corrosive wear and also decreasing adhesion. It was therefore quite unexpected to find that oleic acid could eliminate abrasive wear. A Vickers pump test was run on Bayol 35 containing 200ppm α-Fe_2O_3 and 500ppm oleic acid. Without oleic acid, only 100ppm α-Fe_2O_3 would cause severe abrasive wear, 7079mg. Adding oleic acid reduced the wear to 5mg, Table 17.

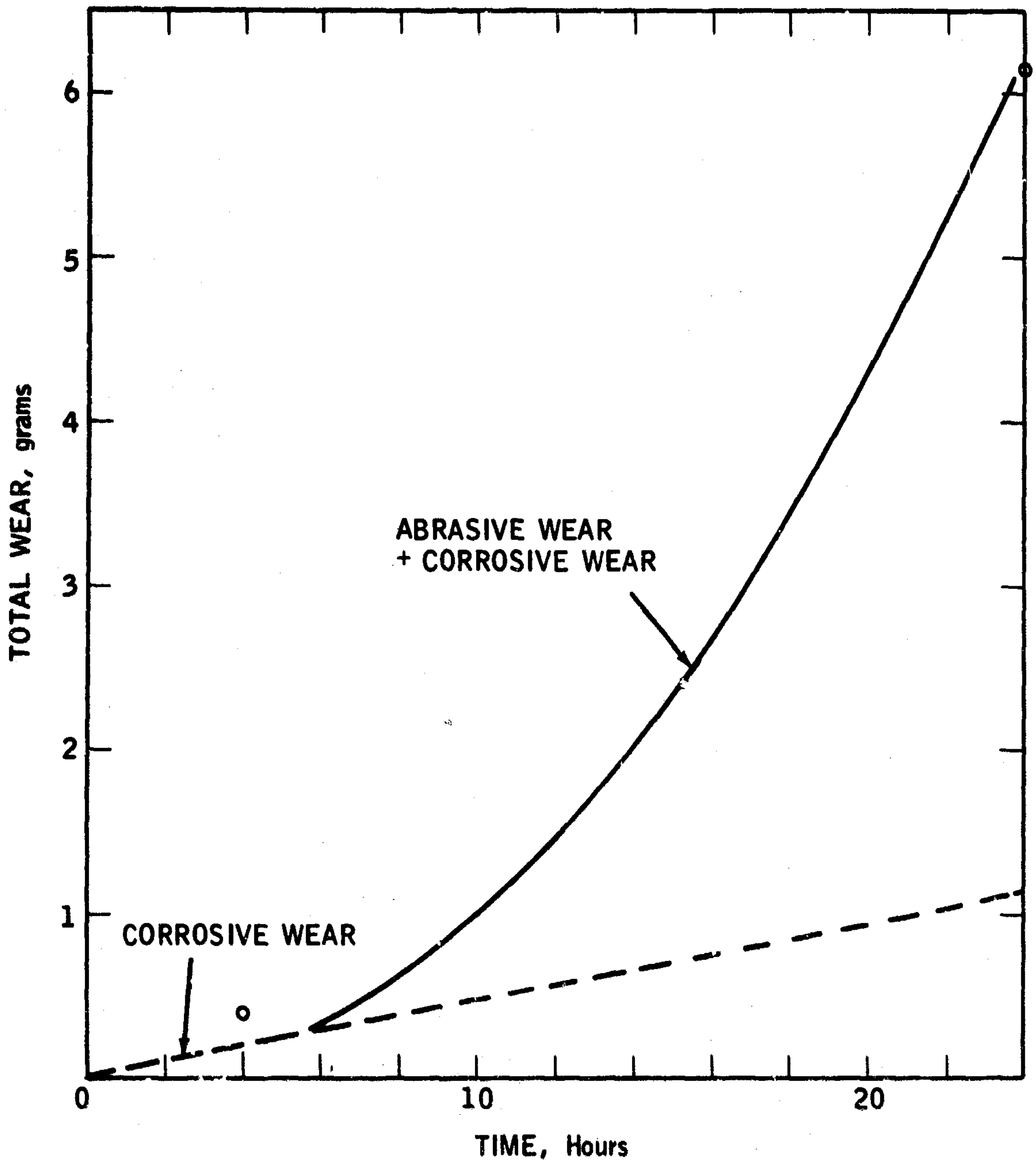


FIGURE 23 - WEAR VERSUS TIME IN A VICKERS VANE PUMP TEST (350psig, 90F, Air)

TABLE 13

EFFECT OF WEAR DEBRIS ON ABRASIVE WEAR

(Vickers Vane Pump Tests, 350psig, 90F, in nitrogen)

Base Fuel: Bayol 35

% of Wear Debris*	None	25%	50%	100%
Wear, mg				
Vane	3	11**	1681	1551
Ring	0	61**	10094	11768
Surface Finish, μ-inch				
Vane, Initial	20	6	6	8
Final	38	7	137	85
Ring, Initial	13	10	33	7
Final	8	33	128	70
Chemical Analyses of Wear Debris, %				
Fe°	--	59.2	87.0	86.4
Fe^{+2}	--	6.6	0.7	0.4
Fe^{+3}	--	13.8	1.1	1.3
Oxygen	--	6.4	6.1	6.2
C	--	0.6	0.3	0.2
H	--	12.2	2.2	1.9

* Wear debris obtained from previous test at 350psig in air. 100% equals 0.16% by weight in the fuel.

** Averages of two runs.

TABLE 14

MATERIAL BALANCES OF ABRASIVE WEAR DUE TO WEAR DEBRIS

	25% Wear Debris	50% Wear Debris
Wear Debris		
Weight, mg	974	13803
% Fe°	59.2	87.0
% Fe Oxides*	32.6	4.0
Fe°, mg	577	12000
Fe Oxides, mg	317	553
Fe° Balance, mg		
From Added Wear Debris	546	1090
From Pump Wear**	72	11775
Total Fe°	628	12865
Fe Oxides Balance, mg		
From Added Wear Debris	368	736

* Summation of % Fe^{+2}, % Fe^{+3} and oxygen.

** If assumed all wear is abrasive; i.e. all Fe°.

TABLE 15

ABRASIVE WEAR BY VARIOUS METALLIC OXIDES*

(Vickers Vane Pump Tests, 350psig, 90F, Nitrogen)

Base Fuel: Bayol 35
Concentration: 100ppm

	None	α-Fe_2O_3	γ-Fe_2O_3	FeO(OH)	α-Al_2O_3	Cu_2O	Fe_3O_4**
Wear, mg							
Vanes	3	942	759	5	114	7	19
Ring	0	7027	7102	27	136	44	6
Surface Finish, μ-inch							
Vanes, Initial	20	6	8	8	13	10	--
	38	139	84	10	74	7	--
Ring, Final	13	8	12	31	11	8	--
	8	59	31	23	76	20	--
Moh Hardness	--	5.6	5.6	--	9	3.5-4	5-6
Crystal Structure	--	Rhombohedral	Cubic	Orhomb	Rhombohedral	Cubic	Spinel
Particle Size, micron (microscopic examination)	--	0.5-1.5	0.5-1	0.5-1	0.3-1	1-5	0.3-0.7

* Iron oxides supplied by courtesy of Columbia Carbon Company.

** 500ppm.

TABLE 16

CONCENTRATION EFFECT ON ABRASIVE WEAR

(Vickers Vane Pump Tests, 350psig, 90F, Nitrogen)

Base Fuel: Bayol 35

	FeO(OH)		Fe_3O_4	
	100ppm	320ppm	500ppm	1000ppm
Wear, mg				
Vanes	5	1169	19	0
Ring	27	9378	6	0
Surface Finish, μ-inch				
Vanes, before test	8	6	--	--
after test	10	151	--	--
Ring, before test	31	12	--	--
after test	23	39	--	--

TABLE 17

EFFECT OF ADDITIVE ON ABRASIVE WEAR

(Vickers Vane Pump Tests, 350psi, 90F, Nitrogen)

	Bayol 35	100ppm α-Fe_2O_3 in Bayol 35	200ppm α-Fe_2O_3 +500ppm Oleic Acid in Bayol 35
Wear, mg			
Vanes	3	942	1
Ring	0	7027	4
Surface Finish, μ-inch			
Vanes, before test	20	6	13
after test	38	139	16
Ring, before test	13	8	18
after test	8	59	14

To try to get some explanation for the effect of oleic acid the solids were filtered out of the fuels and examined under the electron microscope and by I.R. No difference could be noted in the I.R. spectra. The electron micrographs of the oxide particles are shown in Figures 24 and 25. Some differences can be seen. The fuel containing oleic acid showed more clumping of the solid particles and the individual oxide crystals seem less sharp. One can only speculate whether this has any significance.

To summarize the work on abrasive wear, it appears that not enough is known about why particles are abrasive, why there should be a threshold concentration, or why or how additives act to prevent abrasive wear. However, it is not within the scope of this contract to investigate abrasive wear more thoroughly.

FIGURE 24 - ELECTRONMICROGRAPH OF α-Fe_2O_3

FIGURE 25 - ELECTRONMICROGRAPH OF α-Fe_2O_3 AFTER A PUMP TEST WITH OLEIC ACID

VI. FUTURE WORK

Work in the immediate future will be largely limited to studies of scuffing under various conditions. Specifically, this will include:

- The behavior of additives at higher concentrations.
- The effectiveness of other sulfur compounds.
- The effect of higher temperature.
- The relative importance of oxygen and water vapor in the scuffing process.
- The effectiveness of additives on metallurgies other than steel.